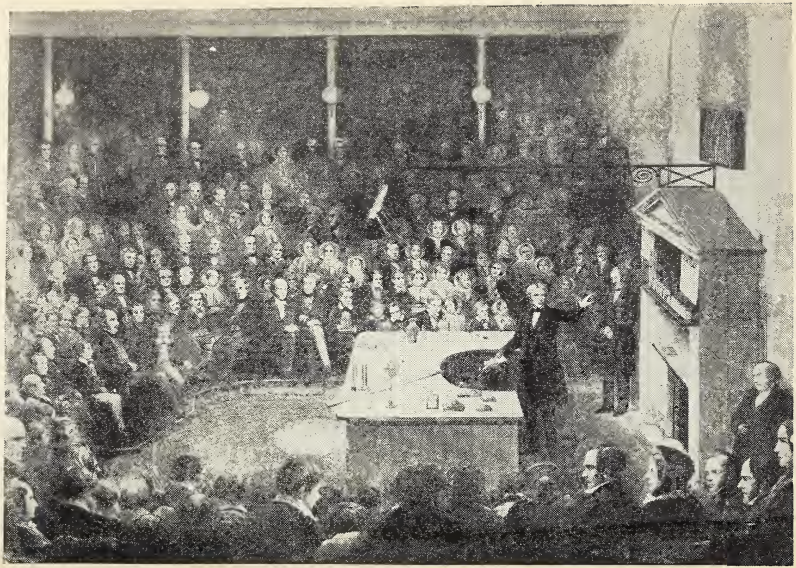
ELEMENTARY PHYSICS



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FARADAY LECTURING AT THE ROYAL INSTITUTION, CHRISTMAS, 1855

ELEMENTARY PHYSICS

By

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PREFACE

As already explained in the preface to *A Junior Physics*, the present volume is the second and concluding part of a concentric course in Physics. The earlier volume is intended for pupils of eleven to fourteen or thereabouts, and it is hoped that its successor will be found suitable for the remaining period of a course which is normally completed at age sixteen.

While there is obviously the closest relation between the two books, I have tried to arrange that the present volume shall at the same time be reasonably independent of its predecessor. Accordingly, most of the chapters which follow will be found to include a brief recapitulation of the corresponding work already done, followed by a fuller treatment of the particular subject in hand. This fuller treatment often involves a greater emphasis on the quantitative and mathematical side. Thus the subjects of Expansion, Thermal Capacity, Latent Heat, Mechanical Equivalent, Refraction, Magnetic Fields, Electric Current, Electrolysis—and the list is by no means exhaustive—can very properly be presented in their simpler qualitative aspects to quite young pupils, but a fuller treatment is needed later, with greater emphasis on the quantitative side.

The book closes with a few pages on the subjects of radiolocation and atomic energy. Obviously nothing more than the merest sketch could be attempted in a volume of this character, but it is good for a boy to realise that all the little fields he has entered in his school studies of Physics are as nothing compared with the vast territory, still largely unexplored, which lies beyond.

I would again like to record my deep indebtedness to Mr. D. H. Turner, B.Sc., formerly my colleague at Hele's School, Exeter, and to my son-in-law, Mr. R. C. Tudway, M.B., B.S., B.Sc., both of whom read through the manuscript and made many valuable suggestions. My son-in-law also gave me much help in reading the proofs. I must also thank the various

authorities concerned for their kind permission to inclu questions set in recent years at the School Certificate Examin tions arranged by the Universities of Bristol, Cambridg Durham, London and Oxford, by the Central Welsh Boar the Oxford and Cambridge Schools Examination Board, ar the Joint Matriculation Board. Finally, I wish to thank number of business firms and private individuals for help securing suitable half-tone illustrations. Their courtesy h been acknowledged on the appropriate pages.

W. LITTLER

Bristol,
Sept. 1948

PREFACE TO SECOND EDITION

IN this edition there is a rather fuller treatment of alternati current, and explanations relating to electrolysis have be brought into line with modern theory. A few addition applications of principles already dealt with (e.g. the ligh meter in relation to photometry) have been given, and th underlying connection between heat, light, 'wireless' tran mission and other phenomena has been discussed and illu trated. In general, the page numbering has been alter either very little or not at all, and there should be no serio difficulty in using this edition side by side with the earlier on

W. LITTLER

Jan. 1955

CONTENTS

PART I

MECHANICS AND HYDROSTATICS

PART II

HEAT, LIGHT AND SOUND

PART III

MAGNETISM AND ELECTRICITY

AP.

Questions

Many of the questions in this book are reproduced fr School Certificate papers of the various examining bodies. T indicate the source the following contractions are used :—

Brist. = *Bristol.*
Camb. = *Cambridge.*
C.W.B. = *Welsh Joint Education Committee.*
Dur. = *Durham.*
Lond. = *London.*
J.M.B. = *Joint Matriculation Board.*
O.C. = *Oxford and Cambridge Schools Examination Board.*
Oxf. = *Oxford.*

The addition of an asterisk (e.g. *Lond.**) means that only pa of the original question has been used.

Often the questions are divided into two groups, A and The 'A' questions are the easier ones.

PART I
MECHANICS AND HYDROSTATICS

CHAPTER 1
VELOCITY

OR at least two thousand years men have interested them-
lves in questions connected with motion. Aristotle, for
istance, made some study of falling bodies, and came to the
onclusion (a wrong one as it turned out) that the rate at which
body falls is proportional to its weight. Thus, according to
im, if a 10-lb. weight and a 1-lb. weight were dropped, the
rst weight would fall ten times as fast as the second. Galileo
564–1642) first cleared the ground for further progress by
roving that Aristotle's conclusion was false, and then set
imself to unravel the whole problem of what we may call the
aw of Falling Bodies. He was greatly handicapped by the
ck of suitable apparatus, but in spite of this, by making
ie best use of what he had, he made marvellous progress. Sir
saac Newton added results and conclusions of his own to
iose obtained by Galileo, and developed the science of
lechanics (which includes the study of Motion) practically to
ie form in which we have it to-day.

Let us begin by thinking of the terms *speed* and *velocity*.
peed, we may say, is *the rate at which a body is changing its
osition*. The question of *direction* does not enter into the
iatter. ***Velocity***, on the other hand, is *the rate at which a
ody is changing its position in a given direction*.

We can illustrate the difference between the two by thinking
f a toy railway train running round a circular track, at a
teady rate of, say, 2 ft. per sec. Its speed is constant, but
s velocity is constantly changing because its direction is
hanging. Strictly speaking, we have not completely stated
he velocity of a body unless we have mentioned *both* its speed

and the direction in which it is moving. All the same, expr sions such as 'a velocity of 10 ft. per sec.' are often met wi In that case it is implied that this movement is taking place a constant direction.

Representation. Velocity is conveniently represented by straight line, the length of the line standing for the magnitu of the velocity, and its direction indicating the direction of t velocity. The 'sense' of the movement (e.g. whether fr east to west or west to east) is usually shown by an arrow. Fig 1/1 two velocities are represented, one of $7\frac{1}{2}$ m.p.h. to t N.E., and another of 5 m.p.h. to the S.E. If OP measured 1 in., the scale would be 1 in. = 5 m.p.h.

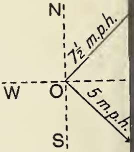


FIG. 1/1

Uniform velocity. *A body is said to move with* **uniform velocity** *when it passes over equal distances in equal intervals of time, however short these intervals may be, the direction remaining constant.*

A motor car travelling north may have completed 30 miles at the end of the first hour, 60 at the e of the second, 90 at the end of the third and so on, yet it practically certain that its velocity has not been constant. will have had to slow down when passing through towns, maki up for lost time when it reaches an open road in the countr All we can say is that its *average* velocity is 30 miles an hour

If, however, the car passes successive milestones at interv of exactly 2 mins., it is getting considerably nearer to o standard of 'uniform velocity.' If, second after second, covers exactly 44 ft. (30 miles per hour = 44 ft. per sec we might then say that its velocity is practically uniform.

Units employed. In the f.p.s. system of units (foot-poun second) velocities are expressed in feet per second, while in t c.g.s. system they are expressed in centimetres per secon The usual 'everyday-life' units, however, are miles per ho and (on the Continent) kilometres per hour.

It is very useful to remember that 60 miles per hour = feet per second. Remembering this, we can very quick reduce such velocities as 30 miles per hour, 10 miles per hou etc., to feet per second.

Space–time diagram. Suppose a man is walking with

niform velocity of 6 ft. per sec. (= 4 m.p.h. approximately). et us express his movement graphically.

We draw two lines at right angles, OX horizontally, and OY ertically. Along OX we indicate time to a scale of, say, 1 in. 1 sec. Along OY we represent distance or 'space.' In this ise a convenient scale would be 1 in. to represent 6 ft.

O represents the point at which we begin to record the an's movement (space and time both zero). After 1 sec. has covered 6 ft., and we get the point A. Similarly we btain B (2 sec. 12 ft.), C, D, etc. By joining all these points e have what is called a 'space–me' or 'displacement–time' irve (or diagram). It can isily be proved that where the elocity is uniform, as in this ise, the space–time diagram onsists of a straight line.

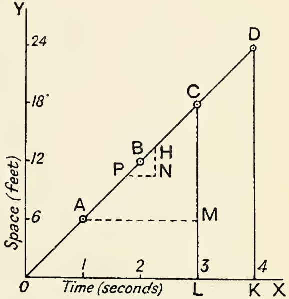


FIG. 1/2

Notice that the velocity, beg *space ÷ time*, is represented y the quotient DK ÷ OK, a uotient known as the *slope* or *radient* of the curve.

Obviously we should obtain ie same answer if we took the uotient CL ÷ OL, CM ÷ AM, r HN ÷ PN, etc. That is because, in the case under conderation, the velocity is uniform.

Variable velocity. Let us now consider the space–time curve r a body travelling with variable velocity. Suppose, for istance, a car starts from rest, and lines are chalked across he road at intervals of 25 ft. It crosses these lines after the ollowing intervals, expressed in seconds: 2·5, 4·2, 5·4, 6·6, 7·6, ·4, 9·2, 10·0. Let us represent a second by half an inch orizontally, and 25 ft. by half an inch vertically. Here is ur curve (Fig. 1/3).

Take the last point on the curve (D), and draw the perendicular DK. DK gives the distance (200 ft.) travelled in he time represented by OK (10 sec.). Thus DK ÷ OK or 00 ft. ÷ 10 sec. = 20 ft. per sec. is the *average* velocity for he whole period.

B

Let us next consider the velocity at a particular instant, s that represented by A, 4·2 sec. after the start. Now, strict speaking, a velocity can only be recorded over an *interval* time, and as an 'instant' is not an interval, it looks at fir sight as though we cannot find the velocity under discussio However, if we consider an *extremely short* interval of tin beginning just before the instant A and ending just after i the velocity during that interval will be for practical purpos the velocity we require, for in such a short interval it wi have had no chance to vary appreciably.

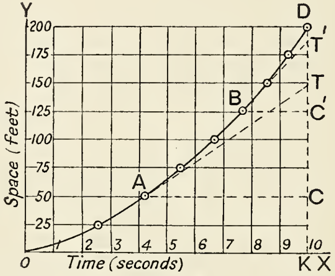


FIG. 1/3

So we may go back to our question—to find the velocity a the instant represented by A. In the space–time diagram o p. 3 we saw that the velocity was given by the *slope* of th curve. Similarly, when the velocity is variable, the velocit at any instant is given by the slope of the curve *at the poin representing that instant.*

Now, the slope of a curve at a particular point is represente by the *tangent* to the curve at that point, so at length we se our way to a solution. Using a ruler as carefully as possibl draw a tangent at A, cutting DK in T. Draw AC parallel t the time-axis, cutting DK in C. Measure TC (= 100 ft.) an AC (= 5·8 sec.). Required velocity in ft. per sec. = 100 ÷ 5·8 = 17·2. Similarly velocity at instant B (i.e. 7·6 sec. fro the start) = C′T′ ÷ BC′ = 65 ft. ÷ 2·4 sec. = 21·1 ft. per se

Example 1. A body is projected vertically upwards, and is und to be 36, 64, 84, 96, 100, 96, 84, 64 *and* 36 *ft. from the ground ter* $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2, $2\frac{1}{2}$, 3, $3\frac{1}{2}$, 4 *and* $4\frac{1}{2}$ *sec., respectively. Construct the ace–time curve for the motion. Explain how the velocity of the dy at any instant can be deduced from the diagram, and in this ay deduce the velocity of the body* (a) $1\frac{1}{2}$ *sec.,* (b) $2\frac{1}{2}$ *sec. after the mmencement of the motion.* Camb.

Choose a suitable scale, say 1 in. to 1 sec. horizontally, and 1 in. 20 ft. vertically. The diagram then appears as shown below. The 'explanation' asked for is as given on p. 4.

$1\frac{1}{2}$ sec. from the com-encement the position of e body is represented by . At A draw the tangent P to the curve, cutting Y in P. Complete the -angled triangle APQ.[1]

Required velocity = AQ PQ = 48 ft. ÷ $1\frac{1}{2}$ sec. = 2 ft./sec.

The second position ($2\frac{1}{2}$ c.) is represented by B. e draw a tangent BP′, ut in this case the vertical ne that would correspond AQ vanishes, the slope zero—and so the velocity = 0.

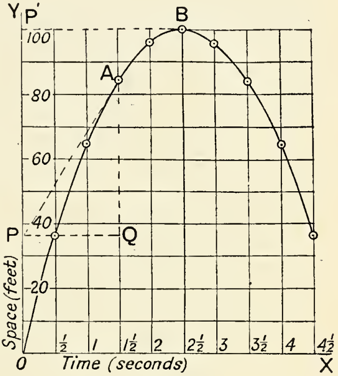


Fig. 1/4

At this point you should ork out an example for ourself, say no. 1 on p. 9.

Component velocities. Suppose a ship is steaming north very ently at 9 ft. per sec., while a man on the deck is walking orth at 6 ft. per sec. At what rate is the man passing some xed point, such as a buoy anchored in the sea?

A moment's thought shows that the answer is 15 ft. per ec. We say that the 9 ft. per sec. and the 6 ft. per sec. are he *component velocities* of the man's motion, and that 15 ft. er sec. to the north is his *resultant velocity*.

When the man has walked to the end of the deck and begins

[1] In Fig. 1/3 the triangle (ATC) was to the right of A and above it, hile in Fig. 1/4 it is to the left and below. This is simply a matter f convenience, and makes no difference to the answer.

to walk at the same pace in the opposite direction, his resultan velocity will be $9 - 6 = 3$ ft. per sec. to the north, th component velocities this time being 9 ft. per sec. to the nort and 6 ft. per sec. to the south.

When from two (or more) given component velocities w find the resultant velocity, we are said to *compound* the tw (or more) given velocities. From the illustration just give we see that when the given velocities are in the same straigh line, the process of compounding is a simple matter of additio or subtraction.

Suppose the man has become tired of walking up and dow the length of the deck and begins to walk across, in an easterl direction, at right angles to the length. What is his resultan velocity now? The problem is evidently not quite so simple

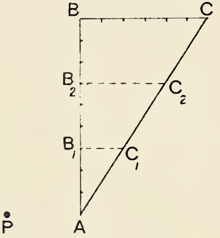


Fig. 1/5

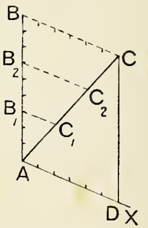


Fig. 1/6

We will suppose that when he begins his cross-deck walk h is at A, exactly opposite a fixed buoy P. *If* he had remaine standing, in 1 sec. he would have been at B, where B is 9 ft to the north of A. Actually, however, his walk has placed him 6 ft. to the right of B, at C. In 1 sec., then, as viewed fro the fixed point P, he has moved from A to C.

Has his movement from A to C been along a straight line Without aiming at a rigid proof, we can obtain a good idea o the answer by considering smaller intervals—$\frac{1}{3}$ sec. In thi time the ship has carried him to B_1, where $AB_1 = 3$ ft., an his walk has placed him 2 ft. to the right of this, i.e. at C_1 Similarly, after $\frac{2}{3}$ sec. he is at C_2. If we make a drawing t scale, we find that AC_1C_2C is a straight line.

Lastly, let us consider the general case in which the two omponent velocities are at *any* angle—the ship moving north s before, the man travelling in a direction parallel to AX. By he time the ship would have conveyed the man 9 ft. to B (if e had been standing still), his actual position is at C where C = 6 ft. and is parallel to AX. It can be shown as before hat the man's movement from A to C has been along a straight ne.

Our results may be summarised in the following important tatement, which is known as the ***Triangle of Velocities.*** *f a body has two component velocities represented by the sides B and BC of a triangle, then its resultant velocity is represented y the third side AC.*

The same truth may be expressed in another form which sometimes convenient. Draw CD parallel to BA, cutting X in D, thus completing the parallelogram ABCD. As efore, AB represents one of the two velocities. This time, owever, we will take AD instead of BC as representing the ther (obviously AD is equal to BC, and is in the same direcion). We may now make the following statement, known as he ***Parallelogram of Velocities.*** *If a body has two component elocities represented by the adjacent sides AB and AD of a arallelogram, then its resultant velocity is represented by the iagonal AC.*

Let us now consider one or two examples.

Example 2. *A man swims across a river* 90 *yds. wide, and hen he reaches the other side he finds he has been carried* 30 *yds. ownstream. The man's speed in still water is* 2 *miles per hour. t what speed is the stream flowing?*

Suppose the man starts from A. He swims t right angles to the stream, but instead of eaching the opposite point B (AB = 90 yds.), e finds he has been carried down to C (BC = 30 ds.).

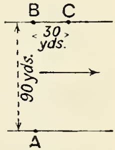


Fig. 1/7

Thus while the man is swimming 90 yds. the tream flows 30 yds. The speed of the stream is herefore one-third of that of the man = $\frac{1}{3}$ of 2 n.p.h. = $\frac{2}{3}$ **m.p.h.**

N.B. Of course the man has covered the distance AC, which s more than 90 yds., but of this, *his* contribution is only AB, while BC is that of the stream.

Example 3. *Continuing the last example, find the direction in which the man must swim in order to reach B, and find how long he will take.*

An observer would notice that the swimmer is *heading* in the direction AD (Fig. 1/8), but that he is actually *moving* in the direction AB. Thus AB may stand for the resultant velocity of (i) the man's own velocity of 2 m.p.h. in the direction AD and (ii) the stream's velocity of $\frac{2}{3}$ m.p.h. in the direction DB.

To obtain the angle DAB, draw DB = $\frac{2}{3}$ (of any unit—say 6 cm., in which case DB would be 4 cm.) and make $\angle DBA = 90°$. From centre D and with radius 2 (of the same unit) describe an arc cutting BA in A. By measurement, $\angle DAB = 19\frac{1}{2}°$. Or by trigonometry, $\angle DAB = \sin^{-1} \frac{2}{3}/2 = \sin^{-1} \frac{1}{3} =$ **$19\frac{1}{2}°$**.

To find the man's time, we can now let AB (in the figure we have just drawn) stand for the width of the stream, 90 yds. By measurement or calculation we find that AD = 95·4 yds. In still water the man would have had to swim this 95·4 yds. at 2 m.p.h., and by arithmetic we find that the required time would be **1 min. 38 sec.**

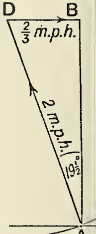


FIG. 1/8

Relative velocity. Closely connected with the subject of component velocities, etc., is that of relative velocity. We may say that **the relative velocity of a body A with respect to another body B** is *the velocity with which A appears to be moving when viewed from B.*

If a train travelling north at 60 m.p.h. is passing a telegraph pole, the pole appears to a passenger to be travelling south at 60 m.p.h. This is the relative velocity of the telegraph pole with respect to the passenger.

If at a junction a train A moving west at 12 m.p.h. is overtaking another train B at 8 m.p.h., the velocity of A relative to B is 4 m.p.h. to the west. If this is not quite clear, draw a diagram for yourself and you will soon see it.

As another example, take the passenger walking across the deck (p. 6, Fig. 1/5). His velocity relative to another (stationary) passenger on deck is 6 ft. per sec. to the east, while his velocity relative to a seagull perched on P would be about 10·8 ft. per sec. in a direction some 34° east of N.

An aeroplane pilot is provided with an air-speed indicator which gives him his speed *relative to the air.* If this becomes too low he is in danger of stalling and then spinning downwards. Accidents have sometimes happened because a pilot flying

ith the wind has adjusted his speed with reference to the *ound.* For instance, if he is flying with a 50 m.p.h. wind id his speed relative to the ground is 80 m.p.h., his speed lative to the air—the point that matters—is only 30 m.p.h. ere is an example involving relative velocity.

Example 4. *A ship is sailing north-west with a velocity of* 10 *.p.h. A passenger on board notices that the wind seems to blow om the north with a velocity of* 15 *m.p.h. Find the true direction id velocity of the wind.*

Consider some smoke coming from the funnel. The motion of the ship would give this an apırent velocity of 10 m.p.h. from the north-west. The wind observed by the passenger is the reıltant of :

(i) the 10 m.p.h. movement from the north-west just noted and
(ii) the actual velocity of the wind.

We therefore draw AB to represent this resulınt (15 m.p.h.) and AC to represent (i). The ctual velocity of the wind is evidently repreınted by CB. By measurement we find that iis is **10·6 m.p.h.,** and that it is blowing from direction **42 degrees east of north.**

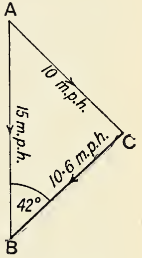


FIG. 1/9

Questions

A

1. A man walks at a uniform pace of 4 m.p.h., but rests for quarter of an hour at the end of the second hour. Draw a space-me diagram to represent his motion.

2. The following velocities are given in miles per hour : 60, 30, 00, 120. Express them in ft. per sec.

3. How many miles per hour correspond to (i) 88, (ii) 22, ii) 132 ft. per sec. ?

4. A ship is steaming along a canal at 6 m.p.h., and a ıan on the ship is walking in the same direction at $3\frac{1}{2}$ m.p.h. Vhat will be the man's velocity relative to a stationary observer n the shore? What will this velocity be when the man turns ound and walks in the opposite direction?

B

1. A body is projected vertically upwards, and its distanc from the ground after $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2, $2\frac{1}{2}$, 3, $3\frac{1}{2}$ and 4 sec. are four to be 28, 48, 60, 64, 60, 48, 28 and 0 ft., respectively. Represe the motion by a space–time diagram, and from the latter fi the velocity of the body after it has been moving (i) 2 se (ii) $3\frac{1}{2}$ sec.

2. An aeroplane is to travel from A to another place B 2 miles due north of it. Assuming the wind to remain consta at 35 miles per hour directly from the east, and the aeroplane have a speed of 125 miles per hour in still air, determine (i) t direction in which the aeroplane has to be steered, (ii) the tin taken to travel the 200 miles. *C.W.B.*

3. What is meant by the *parallelogram of velocities*?

An aeroplane which has a speed of 250 miles per hour, in st air, travels from a point A to a point B which is 400 miles due ea of A. If the wind is blowing from the north at 50 miles per hou determine (a) the direction in which the aeroplane has to b steered, and (b) the time taken to travel from A to B. *C.W.B.*

4. Four ships in convoy are at the corners of a square with sid one mile long. Ship B is due north of A; C is due east of B, a D is due south of C. The four ships are each sailing north at miles per hour. A motor-boat which travels at 26 miles per hou starts at A, delivers a message to B, then to C, then to D, a finally returns to A. The distances between the ships are travers by the shortest possible routes, and no allowance need be ma for time taken in turning.

How far does the convoy advance whilst the motor-boat going round?

Reprinted by permission from The Sunday Times, *in which th question appeared some years ago as a holiday competition.*

5. Define (a) velocity, (b) acceleration.

A mass on a smooth table moves through the following distanc in the stated times. Draw a space–time curve with the times the X-axis, and from it deduce the velocity at time 5·0 sec.

Total time (sec.).	0	1·0	2·0	3·0	4·0	5·0	6·0	7·0
Total distance (cm.) . .	0	10·0	41·0	91·0	162	253	364	495

Camb.

CHAPTER 2

ACCELERATION. FALLING BODIES

may be that you have had the alarming experience of scending a steep hill on a bicycle when something has gone ong with the brakes. If so, you will have gained a very od idea of the meaning of the term *acceleration*, though you ould certainly not be in a state of mind to attempt an exact finition. We will try to arrive at one now, but perhaps two otor-cars will serve our turn better than a runaway bicycle.

Two cars A and B both start from rest. In 10 sec. A has quired a velocity of 30 m.p.h., but it takes B 20 sec. to quire this same velocity. A, then, has increased its velocity 30 m.p.h. in 10 sec., so that its average rate of increase is m.p.h. per sec. B has increased its velocity by 30 m.p.h. in sec., its average rate of increase being $1\frac{1}{2}$ m.p.h. per sec. ecause A is increasing its velocity at a more rapid rate than we say that its acceleration is greater. In fact *the* ***accelera-*** *n of a body* is *the rate at which its velocity is increasing.*

It follows from our definition that if the velocity is decreas- g, the acceleration is negative. A negative acceleration is ten known as a *retardation.*

Acceleration is said to be *uniform* when the velocity changes ually in equal intervals of time, however short these intervals ay be. In the present chapter it is to be understood that celeration is uniform, unless something is said or implied the contrary.

Example 1. *A train increases its velocity from* 10 *m.p.h. to m.p.h. in* 5 *mins. Find its average acceleration* (i) *in m.p.h. r min.,* (ii) *in ft. per sec. per sec.*

(i) The velocity has increased by 20 m.p.h. in 5 mins. This is at the rate of **4 m.p.h. per min.**

(ii) 4 m.p.h. per min. $= \frac{88}{15}$ ft. per sec. per min.
(for 60 m.p.h. $=$ 88 f.p.s., and 4 m.p.h. $= \frac{1}{15}$th of this).

If $\frac{88}{15}$ ft. per sec. is the increase of velocity per *minute*, the crease per *second* will be $\frac{1}{60}$th of this.

$\therefore$ acceleration $= \frac{1}{60} \times \frac{88}{15} =$ **0·098 ft. per sec. per sec.**

Notice how the answers are expressed, (i) miles per hour p minute; (ii) feet per second per second. People are sometim puzzled to find that a unit of time is mentioned twice. It mentioned first, of course, to indicate how much velocity h been added on (e.g. '4 miles per hour'), and afterwards to gi the rate at which that increase has been taking place ('p minute'). For shortness, 0·098 ft. per sec. per sec. would oft be written 0·098 ft./sec.^{2}

***Example* 2.** *A train travelling at* 60 *m.p.h. is brought to rest the action of its brakes in* 2 *minutes. Find the average accelerati in ft./sec.*^{2}

Here the acceleration is obviously *negative*.

$$60 \text{ m.p.h.} = 88 \text{ f.p.s.}$$

$$\begin{aligned} \therefore \text{ loss of velocity} &= 88 \text{ ft. per sec. in 2 mins.} \\ &= \tfrac{88}{120} \text{ ft. per sec. per sec.} \\ &= 0{\cdot}73 \quad ,, \quad ,, \\ \text{i.e. acceleration} &= -\mathbf{0{\cdot}73\ ft./sec.^2} \end{aligned}$$

(We could have said *retardation* $= 0{\cdot}73$ ft./sec.^{2}, but this less usual.)

Velocity–time curves. On p. 3 we made a displacemen time (or space–time) curve. Let us now make a few velocit time curves and see what can be learnt from them.

We will begin with the case of a body moving with a co stant velocity (i.e. acceleration = 0) of 5 ft. per sec., for 6 sec.

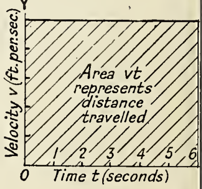


FIG. 2/1

The 'curve' is a straight line parallel to the time-axis, i.e. the *slope* = 0. This is because there is no change in the velocity, i.e. *acceleration* = 0. We shall see presently that the slope is always a measure of the acceleration.

The distance travelled by a body moving for 6 sec. at 5 ft. per sec. would evidently be 6 × 5 30 ft. On our graph this distance is represented by the shad *area* under the curve.

We will next consider the velocity–time curve for a bo

›ving with a constant acceleration (other than zero). Here :he necessary data for a body thrown upwards with a velocity 100 ft. per sec. (we shall see later that the acceleration in :h a case is constant and $= -32$ ft./sec.^{2}).

Time (sec.)	0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4
‌pward velocity (ft./sec.) . .	100	84	68	52	36	20	4	−12	−28

Constructing the curve, we have the figure given ow :—

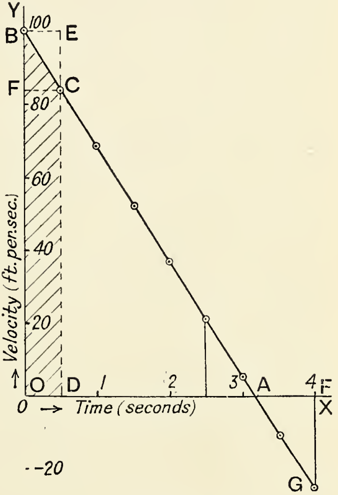


Fig. 2/2

i) The first obvious int is that our 'curve' again a straight e. This is a mathe-tical consequence of fact that for equal anges in the time (0, 1, $1\frac{1}{2}$ . . .) we have ual changes in the ocity (100, 84, 68, . . .), i.e. of the t that the accelera-n is uniform.

(ii) In our space–time ph (p. 3) we saw that m the slope we ob-ned the quotient *inge of position* ÷ *e*, i.e. *velocity*. Simi-ly, from the slope of r velocity–time graph obtain the quotient *inge of velocity* ÷ *time*, i.e. *acceleration*.[1]

Thus, taking the slope as OB ÷ OA, we get acceleration

[1] Thus in Example 1 (p. 11) we obtained the acceleration (4 m.p.h. min.) by dividing the change of velocity (20 m.p.h.) by the time mins.).

$= -100$ ft./sec. $\div 3\frac{1}{8}$ sec. $= -32$ ft./sec.^{2} (We write *mi* 100 because the velocity is decreasing.)

(iii) Consider a small portion of the curve on the l between OB and the point C (where velocity $= 84$ ft./s and time $= \frac{1}{2}$ sec.). From C drop a perpendicular CD the time-axis. Produce DC to E, and draw BE and parallel to OD.

At the beginning of the half-second the velocity was ft./sec. If it had remained at this value the distance travel would have been $100 \times \frac{1}{2} = 50$ ft. This would have b represented by the area OB $\times$ OD, giving the rectangle OBE

On the other hand, if the velocity throughout had been same as at the *end* of the interval (84 ft. per sec., represen by DC) the distance would have been $84 \times \frac{1}{2} = 42$ ft. T would have been represented by the area OFCD.

For practically the whole interval of half a second, howe the velocity has been less than 100 but greater than 84. T the distance travelled is less than 50 (the rectangle OBE but greater than 42 (rectangle OFCD). It is actually re sented by the intermediate area, OBCD[1], which in Fig. is indicated by shading.

This is the distance travelled in the first half-seco Continuing in the same way, we see that the distance travel in $3\frac{1}{8}$ sec. (which brings us to the point A) is represented the space OAB.

What about the area AGF (between $3\frac{1}{8}$ sec. and 4 se This lies *below* OX, indicating that the velocity through the interval is *negative*.

This corresponds to the physical fact that the body thro upwards has reached its highest point (at A, velocity = and is now descending. If its upward velocity is recko positive, clearly its downward velocity is negative. He the area AGF represents a negative distance—the mov body is 'turning back on its tracks.'

The actual distance travelled in the first 4 sec. is represent then, by the area OAB *minus* the area AGF.

[1] This is not a rigid proof. By taking DC infinitely close to however, it can be proved that the space described is really represe by the area OBCD, even though the complete 'curve' is not a strai line.

\s a last velocity–time curve let us take a case in which acceleration is variable. We have abundant illustrations the movement of a motor-car. Thus from rest to 30).h. we usually have rapid acceleration, while from 50).h. to 60 m.p.h. acceleration would be much slower. If car pulls up sharply, acceleration is very rapid, but ;ative. If it maintains a steady velocity of 40 m.p.h. some distance, acceleration is zero, and so on.

.et us take the following case.

Time (sec.)	0	1	2	3	4	5	6	7	8
elocity (ft./sec.) .	0	10	17	23	28	32	35	37	38

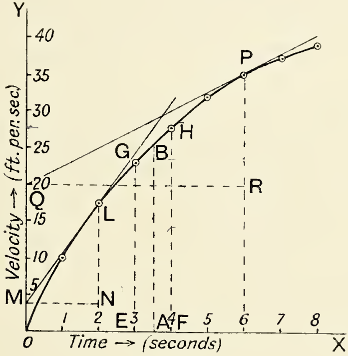


Fig. 2/3

[t will give point to our study of this curve if we try to swer the following questions:—

(i) What is the velocity at $3\frac{1}{2}$ sec. from rest?

(ii) How far did the body travel in the fourth second?

(iii) How far did it travel in the first 4 sec.?

(iv) What is its acceleration (*a*) 2 sec., (*b*) 6 sec. after starting?

(i) Mark the point $3\frac{1}{2}$ sec. (A), draw the perpendicu AB and measure it. It indicates a velocity $25\frac{1}{2}$ ft. per sec.

(ii) Mark the end of the third second (E) and of the fou (F). From E and F draw perpendiculars EG a FH to the time-axis, cutting the curve at G and The area GEFH gives the distance travelled in fourth second. This area may be obtained either calculation—it is practically equal to EF $\times$ $\frac{1}{2}$(GE HF)—or by counting squares, and indicates distance of $25\frac{1}{2}$ ft.

(iii) The distance travelled in the first 4 sec. is represen by the area OFH and (by counting squares otherwise) is found to be 64 ft.

(iv) The acceleration 2 sec. after starting is found drawing the tangent LM and measuring the sl LN $\div$ MN $= 12\frac{1}{2} \div 2 = 6\frac{1}{4}$ ft./sec.^{2}

Similarly the acceleration 6 sec. after starting = PR QR $= 15 \div 6 = 2\frac{1}{2}$ ft./sec.^{2}

Falling bodies. In the opening paragraph of this book saw that the subject of falling bodies forms a landmark in history of science. Galileo proved that in this matter ideas of Aristotle were wrong, and if he was wrong in point he might be wrong in others. The last word in scie had evidently not been said, and men felt encouraged make experiments for themselves with a view to un standing the hidden laws of nature.

But though Galileo had found what the law of fall bodies was *not*, he was far from having found what it *w* Clearly the farther the body fell, the greater was the veloci and at first he asked himself whether the velocity might be p portional to the distance fallen—whether, for instance body after falling 100 ft. would have twice the velocity t it had after falling only 50. By a process of reasoning a without actual experiment, he satisfied himself that this v not the case.

If the velocity acquired is not proportional to the distan is it proportional to the time? In other words, is the celeration uniform? Galileo was able to prove mathematic

t *if* this is the case, *then* the distance fallen would be portional to the square of the time; that, for instance, body would fall nine times as far in 3 sec. as it would in ec. This was the point he had to settle—by experiment.

The difficulties were very great. A falling body soon gins to move so rapidly that accurate timing is nearly possible even with a modern stop-watch—and the only tches available in Galileo's day were very clumsy affairs.

He got over the difficulty of rapid movement in this way. I made the body run down an inclined plane instead of ling vertically,' he argued, 'the whole movement would be wed down, but the same law would be at work—the distance velled would still be proportional to the square of the time.' proposed, so to speak, to *dilute* the force of gravity.

But without a good watch how was he to measure time? He filled a large vessel with water and made a pin-hole in bottom, so that the water could drip out. He collected s water in a weighed dish, and then the weight of the water s a measure of the time.[1]

So he took a board about 23 ft.[2] long, and in it made a oove about an inch wide.[3] The groove was straight and ooth, and was covered with very smooth parchment. tilted the board slightly, and found the time required for polished brass ball to roll down, for instance, (*a*) the full gth of the board, (*b*) a quarter of that length. He found t the first time was just twice the second, i.e. the distance velled was proportional to the square of the time. To ote his own words, 'We repeated this experiment more n once, in order to measure the time with an accuracy h that the deviation between two observations never eeded one-tenth of a pulse-beat . . . in such experiments, peated a full hundred times, we always found that the spaces versed were to each other as the squares of the times, d this was true for all inclinations of the plane. . . .

Provided the level of the water in the large vessel was kept constant. lileo does not say whether he attended to this point.

'12 cubits.' Torricelli gives the height of his barometer, which uld be about 30 in., as 'a cubit and a quarter and an inch over.' is an interesting little exercise in arithmetic to calculate, from this, equivalent of 12 cubits.

'A little more than one finger in breadth.'

The water thus collected was weighed, after each desc on a very accurate balance; the differences and ratios of tl weights gave us the differences and ratios of the times, this with such accuracy that although the operation repeated many, many times, there was no appreciable crepancy in the results.' [1]

Modern forms of experiment. The obvious modern f of Galileo's experiment is to use a stop-watch or stop-cl instead of his dripping-water method. A grooved bo 8 or 10 ft. long can be prepared without great difficulty, marked off into lengths of 1 ft. with pencil or chalk. W a little practice, the times required to traverse 1, 2, 3 . . . can be found with very fair accuracy, the time in each being taken as the mean of several values. The resu could evidently be expressed as a space–time curve (p. but it will be more to our present purpose to plot the 'spa against the *square* of the time.

Thus, suppose we have obtained results corresponding the first two rows in the following table. We find t^2

Length (ft.).	1	2	3	4	5	6	7	8	9	1
Time (t) (in sec.)	3	$4\frac{1}{5}$	$5\frac{1}{5}$	6	$6\frac{3}{5}$	$7\frac{2}{5}$	8	$8\frac{2}{5}$	9	9
t^2 .	9·0	17·6	27·0	36·0	43·6	54·8	64·0	70·6	81·0	88

arithmetic, and then obtain the graph shown in Fig. 2/4. The fact that the graph is a straight line proves that the distance travelled is proportional to the *square* of the time, and this in turn requires that the acceleration shall have been uniform. This uniform acceleration to which a freely falling body is subject is known as g.

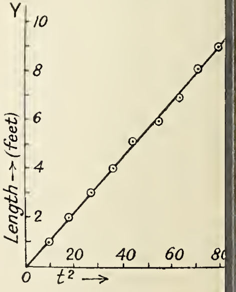


FIG. 2/4

How Aristotle was misled. We have all noticed that a penny

[1] Quoted from Magie, *Source Book in Physics.*

s to the ground a great deal faster than a piece of paper, l that very light particles such as dust fall very slowly eed. We can therefore hardly blame Aristotle for conding that heavy bodies fall more quickly than light ones, he was certainly taking far too much for granted when assumed that the rate of fall is actually *proportional* to weight.

The point he overlooked was the part played by the *air*. t were not for this, a piece of paper would fall to the ground t as quickly as a penny.

To prove it, cut out a circle of paper a shade smaller than penny. Lay it on the coin, hold the latter horizontally ween thumb and finger, and then let it drop. Paper and nny both reach the floor at the same instant.

f the penny had been uppermost, we might have argued t it had simply pushed the paper in front of it; but the ny was underneath.

What has happened is that the penny has pushed the air of the way, and then the paper, relieved of the resistance the air, has fallen just as fast as the penny.

Boyle placed a leaden bullet and a piece of paper in the eiver of his air-pump—the receiver in this case being a g tube—and pumped out the air. He then quickly turned tube upside down, and noted that bullet and paper ched the bottom at the same time. Newton did a similar periment with a guinea and a feather. Experiments of same sort can easily be done in school if an air-pump is ailable.

The reason why heavy bodies and light bodies are all bject to the same acceleration will be better understood en we come to the next chapter, but we can obtain a gh idea now. Suppose a penny weighs 100 times as ch as a circle of paper. In that case the force pulling it wnwards is 100 times the force acting on the piece of paper, d we feel that it ought to move faster.

But is it not possible that the penny contains 100 times much *stuff* or *matter* as the paper? In that case, the larger ce acting on the larger amount of matter, might produce ly the same acceleration as the smaller force acting on the aller amount.

Determination of g. The value of g can be found v accurately by means of the pendulum, with which you h probably made experiments. It consists of a heavy b tied to the end of a piece of thread, and you will have fo that the time of swing does *not* depend on the weight of bob, nor on the amplitude of the swing (i.e. on the dista from the central position of the bob to the extreme left right). It *does* depend, however, on the length, the ti being proportional to the square root of the length ($t \propto \sqrt{}$ It can be proved in fact that

$$t = 2\pi \sqrt{\frac{l}{g}}$$

where t is the time of swing in seconds, $\pi = 3{\cdot}14$, l is length of the pendulum in centimetres, and g is the accelerat due to gravity, in cm. per sec. per sec.

According to this equation, an increase in the value would cause t to be reduced. This seems to be reasonable. For suppose the bob to be at A in its extreme left position. It begins to move along the path AV, and the speed with which it moves along this downward path will depend on the acceleration due to gravity. The greater this is (i.e. the greater the value of g), the more quickly will the bob move downwards (i.e. the smaller the value of t).

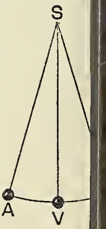


Fig. 2/5

So to find the value of g, we make a pendulum and measure l (SV in Fig. 2/5) in centimetres. We then take the time of (say) 20 swings in seconds, and dividing by 20 we obtain the value of t. Kn ing t, π and l, we can obviously calculate g.

Actually, the value of g at Greenwich is $981{\cdot}18$ cm. sec. per sec. or $32{\cdot}19$ ft. per sec. per sec. In all ordin calculations the values are taken as 981 and 32, respectiv and these are the only numbers in this paragraph that n be remembered.

It is interesting to notice that at the equator $g = 978{\cdot}$ while at the North Pole it is $983{\cdot}21$. This is because, ow to a slight flattening at the poles, the distance from the eart centre is a little less at those points, and so the force of grav

a little greater. Similarly, while the value is 981·18 at eenwich, it is 981·37 at Manchester, 200 miles farther north. For the same reason (i.e. increased distance from the earth's itre), the value of g might be expected to fall very slightly th increased height above sea-level, and this is found to be so.

Uniformly accelerated motion—Equations. Suppose that a certain instant a body has a velocity u (represented by ι in the velocity–time graph of Fig. 2/6) and that it has a iform acceleration a.

After 1 sec. its velocity will be $u + a$.
,, 2 sec. ,, ,, $u + 2a$.
,, 3 sec. ,, ,, $u + 3a$.
. . . .
. . . .
,, t sec. ,, ,, $u + ta$.

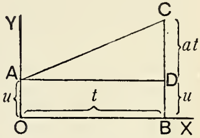


FIG. 2/6

this velocity is denoted by v, we may write $\boldsymbol{v = u + at}$. (1)

It is represented in our graph by the line BC.

Draw AD parallel to the time axis cutting BC in D.

Then BD = OA = u.

$\therefore$ DC = BC − BD = $(u + at) - u = at$.

The velocity–time graph is AC, and as the acceleration is iform, AC is a straight line.

The distance s described in time t is represented by the area)BC (p. 14).

Now area AOBC = rect. AOBD + $\triangle$ ADC

$$= (\text{OA} \times \text{OB}) + \tfrac{1}{2}\,\text{AD} \times \text{DC}$$
$$= (u \times t) + \tfrac{1}{2}\, t \times at\ *$$
$$\text{i.e. } \boldsymbol{s = ut + \tfrac{1}{2} at^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

s may be expressed in another way, for DC = BC − BD = − u. Giving this value to DC, the line marked with an terisk becomes $(u \times t) + \frac{1}{2}\, t \times (v - u)$

$$\text{i.e. } s = ut + \tfrac{1}{2}\, vt - \tfrac{1}{2}\, ut$$
$$= \tfrac{1}{2}\, ut + \tfrac{1}{2}\, vt$$
$$\text{or } \boldsymbol{s = \tfrac{1}{2}(u + v)t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Lastly, from (1) we have $v - u = at$

and ,, (3) ,, $v + u = \dfrac{2s}{t}$

Multiplying together, we have $\boldsymbol{v^2 - u^2 = 2as}$ . . . (4)

Equations 1, 2, 3 and 4 can be used to solve any probl on uniformly accelerated motion, and they should be carefu committed to memory.

Motion from rest. In the case just discussed, the body w already travelling with velocity u when we began to ta notice of its motion. Very often, however, it happens th we are considering the uniformly accelerated motion of a bo starting *from rest*. In that case $u = 0$ and our equations ((2), (3) and (4) become respectively

$$v = at \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a$$
$$s = \tfrac{1}{2}\, at^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2a$$
$$s = \tfrac{1}{2}\, at \ \ vt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3a$$
$$\text{and } v^2 = 2\, as \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4a$$

We will now work through a few typical examples of uniforn accelerated motion.

Example 1. *A body falls from rest for $1\frac{1}{2}$ sec. What velocity w it have acquired, and how far will it have fallen?*

We have $u = 0$, $a = 32$. $t = 1\frac{1}{2}$. $v = ?$ $s = ?$

Using the equation $v = u + at$

we have $v = 0 + 32 \times 1\frac{1}{2}$

$= $ **48 ft. per sec.**

Also from $s = \frac{1}{2}(u + v)t$

we have $s = \frac{1}{2}(0 + 48) \times 1\frac{1}{2}$

$= $ **36 ft.**

Sometimes we can manage quite well without a formula. this case for instance,

Acceleration $= 32$ ft. per sec. per sec.

$\therefore$ in $1\frac{1}{2}$ sec., velocity acquired $= 1\frac{1}{2} \times 32 = $ **48 ft. per sec.**

As the velocity of the body is 0 to begin with, and increa uniformly to 48 ft. per sec., the *average* velocity is $\frac{1}{2}(0 + 48) =$ ft. per sec.

Distance fallen in $1\frac{1}{2}$ sec. at an average velocity of 24 ft. sec. $= 1\frac{1}{2} \times 24 = $ **36 ft.**

Example 2. *A body is thrown upwards with a velocity of 80 per sec. How far will it rise? Find its velocity* (a) *when half time has elapsed,* (b) *when it has attained half its full height.*

[T]he first two answers are easily obtained without the use of [for]mulæ, thus:—

[T]he body *loses* a velocity of 32 ft. per sec. every sec.

$\therefore$ to lose the whole of its velocity, no. of sec. required $= 80 \div 32 = 2\frac{1}{2}$.

[I]ts average velocity will be $\frac{1}{2}(80 + 0) = 40$ ft./sec.

$$\therefore \text{ height attained} = (\text{average vel.}) \times (\text{time})$$
$$= 40 \times 2\tfrac{1}{2}$$
$$= \mathbf{100\ ft.}$$

[W]hen half the time has elapsed, it will have lost half its velocity, [wh]ich will therefore be reduced to **40 ft. per sec.**

[F]or the last part, it is easier to use a formula.

[W]e have $u = 80$. $s = 50$. $a = -32$. $v = ?$

[T]he formula connecting these quantities is $v^2 = u^2 + 2as$.

$$\therefore \quad v^2 = 80^2 + 2(-32) \times 50$$
$$= 6400 - 3200$$
$$= 3200$$
$$\therefore \quad v = \sqrt{3200} = \mathbf{56{\cdot}6\ ft.\ per\ sec.}$$

(Although acceleration here is negative, the formula is un[alt]ered. It still reads $v^2 = u^2 + 2as$, but we substitute -32 for a.)

Example 3. *A stone was thrown vertically upwards from the top [of] a cliff. After 8 sec. it passed the top of the cliff as it descended, [an]d 3 sec. later fell into the sea below. Find the height of the cliff.*

[T]he stone has evidently taken 4 sec. to reach its highest point, [i.e.] its initial velocity is reduced to zero in 4 sec.

[B]ut loss of velocity per sec. $= 32$ ft. per sec.

$\therefore$ initial velocity (upwards) must have been $4 \times 32 = 128$ ft. [per] sec.

(This could also be easily obtained from the formula $v = u + at$, [pu]tting $v = 0$, $a = -32$, $t = 4$, $u = ?$).

[A]s it passes the cliff, the stone will have a *downward* velocity [of] 128 ft. per sec. and 3 sec. later this will have increased to [12]8 $+ (32 \times 3) = 224$ ft. per sec.

$\therefore$ *average* velocity on this journey from cliff to sea $= \frac{1}{2}(128 + [22]4) = 176$ ft. per sec.

[T]he stone travels with this average velocity for 3 sec.

$\therefore$ height of cliff $= 176 \times 3 =$ **528 ft.**

(Or we might say, $u = 128$, $a = 32$, $t = 3$, $s = ?$ and use the [for]mula $s = ut + \frac{1}{2}at^2$.)

Object thrown horizontally. It is an interesting exercise [to] trace the path of a stone thrown *horizontally* from the edge [of] a high cliff with a given velocity. Suppose the latter

is 40 ft. per sec. and we wish to find the position of the b
after $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2 . . . sec., air resistance being neglected.

We will work out the '2 seconds' case, because as numbers are fairly large, they will show more clearly in diagram.

A is the point from which the body is thrown. Its ini *downward* velocity is 0, and from the formula $s = ut + \frac{1}{2}$ we easily calculate that if there had been no outw motion it would have reached B_1, where $AB_1 = 64$ ft.

Its horizontal velocity is 40 ft. per sec. (unchanging, if we neglect air resistance), so after 2 sec., if there had been no downward motion, it would have reached B_2, where $AB_2 = 80$ ft. Clearly its actual position will be at B, 64 ft. below B_2.

Work out the other positions for yourself. You should obtain a curve such as is shown in Fig. 2/7.

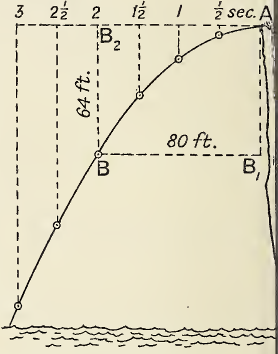


FIG. 2/7

Questions

A

1. A train increases its velocity from 10 m.p.h. to 60 m. in 10 mins. Find its average acceleration, (i) in m.p.h. per min (ii) in ft. per sec. per sec.

2. A stone is falling with an acceleration of 32 ft./se Express this acceleration in ft. per sec. per minute.

3. A body projected vertically upwards with a velocity of 80 per sec. has the following velocities at the times mentioned:—

Time (sec.).	0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5
Upward velocity (ft./sec.)	80	64	48	32	16	0	−16	−32	−48	−64	−

Construct the velocity–time curve, and from it find (i) acceleration, (ii) the distance travelled in $2\frac{1}{2}$ sec.

B

1. Explain the terms *velocity*, *uniform velocity*, *average velocity*. A motor-car moving with a velocity of 24 ft./sec. is uniformly celerated at 2 ft./sec.^{2} for 20 sec., and is then uniformly retarded as to come to rest after a further 16 sec. Plot the velocity–ne graph of the motion, and use the graph to determine (*a*) e total distance travelled, (*b*) the average velocity of the car. *O.C.*

2. A constant braking force is applied to a train, so reducing iiformly its velocity of 44 ft. per sec. by 8 ft. per sec. every sec. Compile a table showing at the end of successive 10 sec. to 50 sec. (*a*) the velocity, (*b*) the total distance travelled by e train from the application of the brakes.

On the same axes plot a velocity–time graph and a distance–ne graph, and on them indicate (i) the time taken to come to st if the brakes are kept on, (ii) the distance travelled during at time. Also determine these values by calculation. *Lond.*

3. Explain how you would use the velocity–time graph for a oving body to deduce (*a*) the acceleration at any instant, (*b*) e space described during any interval of the period for which e graph is drawn.

A stone is thrown vertically upwards with a velocity of 80 /sec. Plot a velocity–time graph for the first 5 sec. of the otion, and find from the graph the greatest height reached. = 32 ft./sec./sec.) *Oxf.*

4. Define uniform acceleration and describe an experiment to d *g*, the acceleration due to gravity.

A body is projected vertically upwards from the ground and aches a height of 625 ft. Find the velocity of projection and e time to rise to the highest point. *Lond.*

5. An aeroplane flying horizontally at 240 miles per hour at a ight of 5000 ft. releases a bomb. Neglecting air resistance, lculate (*a*) the time which elapses before the bomb hits the ound, and (*b*) the horizontal distance travelled by the bomb fore the impact. *O.C.*

6. A shell is fired vertically with a velocity of 400 ft. per sec. ow high will it rise, and after what time will it reach this aximum height? *O.C.*

7. A cricket ball is thrown vertically upwards with a velocity 96 ft. per sec. Calculate how far it will rise and how long will apse before it again hits the ground.

8. From a balloon ascending with a vertical velocity of 16 ./sec., a stone is let fall which reaches the ground in 10 sec. eglecting friction, find the height of the balloon when the stone released.

CHAPTER 3

NEWTON'S SECOND LAW OF MOTION

We would all agree that if a brick (or any other object) lying on the ground, it will remain exactly where it is unl some force is applied to it. Perhaps we are not so sure th if a body is *moving* in a straight line—a cricket ball rolli over the ground, for instance—it will continue moving ever, with the same velocity, unless some force is appli to it. Our cricket ball soon comes to rest because of the fo of *friction*. If we could make a 'cricket ball' of smooth i and bowl it along the smooth surface of a frozen lake, would continue to move for a much longer time, because have greatly reduced the force of friction. But we cann get rid of this force altogether—and there is always t frictional resistance of the air. However, thinking al these lines, it is not hard to realise that if our moving cricl ball could be set *completely* free from resisting forces it wou continue to move for ever with unchanging velocity. T ideas we have thus briefly discussed are summed up in Newto ***First Law of Motion***, which states that *A body in a st of rest or of uniform motion in a straight line will continue that state of rest or motion unless it is acted upon by some extern force.*

In short—no force, then no change of motion.

If change of motion is produced only by force, we oug somehow to be able to measure force by the change of moti it produces. Let us follow up this idea and see where leads us.

Two boys of equal size are in two quite similar rowi boats. They start together, working their hardest, and 30 sec. A has attained a speed of 3 m.p.h. B takes 50 sec. acquire the same speed. Quite rightly, we conclude that has exerted more force than B. Force, then, is measu not simply by the velocity it imparts to a body, but by t *rate* at which the velocity is imparted—in short, by t acceleration.

Let us start A and B off once more, but this time we will ovide A with a good heavy cargo, so that he has to propel much greater mass than B. Once again both row their rdest, but this time A takes 50 sec. to acquire a speed of m.p.h.—the same time as B.

In this case also we conclude that A has exerted more ce than B, because though he has produced only the same celeration, his force has been applied to a larger mass.

If, then, we are to estimate force by the motion it produces, must take into account: (i) the *mass* of the body to which e force is applied, and (ii) the *rate* at which it causes the locity of the body to increase.

Mass and velocity are very conveniently combined in the m *momentum*, which means the product of the two. Thus seems that a force might be measured by applying it to a dy and noting the rate at which the *momentum* of that dy is increased. To go back to our illustration, A's rate increase of momentum was greater in both cases. In the st he was dealing with the same mass as B, but caused its locity to increase at a greater rate. In the second he was aling with a greater mass, and caused its velocity to increase the same rate.

Let us now try to obtain more exact information on the o points mentioned, to obtain, in fact, the answers to ese two questions:—

(i) What is the exact relation between the force applied to a body of given mass and the acceleration it produces?

(ii) Suppose the same force is applied to successive bodies of different mass, what will be the relation between the various accelerations produced and the respective masses?

The apparatus most commonly used in dealing with these estions is known as *Fletcher's Trolley*, so we will begin by scribing it.

The trolley itself consists of a block of wood about 2 ft. ng mounted on wheels, which turn with very little friction. t right angles to its length it is drilled with holes which rry several steel cylinders S_1, S_2. . . . These serve to weight e block, and also enable us to vary its mass when required.

The trolley runs over a base-board, the surface of which very smooth and hard—in fact, it is usually faced with st with grooves for the trolley wheels. A cord is attached the trolley and passes over a pulley, afterwards being attacl to a light cardboard box in which weights may be placed, causing the trolley to move.

Near the back is a fixed iron pillar to which is clampe straight, steel spring which can be made to vibrate in horizontal plane. By altering the setting, the vibrat portion can be made longer or shorter, and thus the per of vibration can be adjusted to $\frac{1}{5}$th sec., $\frac{1}{8}$th sec., etc. N

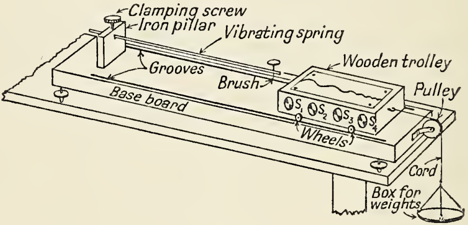


Fig. 3/1

the free end is a small brush, which is dipped in ink from ti to time. A strip of paper is pinned on the top of the troll and as the spring vibrates while the trolley is moving forw the brush traces a wavy line.

We begin our experiment by so arranging the conditi that when the trolley is made to move forward with a sli tap, it shall continue to move with uniform velocity. T is done by putting a small weight (2–5 gm.) in the box (j short of what is needed to make the trolley move as requir completing the adjustment by a turn of the rear screw of base-board. When the adjustment is correct the wa traced on the paper will be of equal length (Fig. 3/2*a*).

We may now consider that our block is free from the act of outside forces. Of course we cannot quite elimin friction, but the frictional forces are neutralised by the sli screw motion and by the weight we have put in the box.

We can now attempt to answer question (i)—to find

xact relation between the *force* applied to a body of given ass and the *acceleration* it produces.

We put a certain weight, say 10 gm. in the box (additional the 2–5 gm., already there), start the trolley, and obtain a urve such as Fig. 3/2*b*.

This 10 gm. was, of course, the 'applied force.' [1]

We now repeat the process using 20 gm. instead of 10 gm., nd obtain Fig. 3/2*c*.

In Fig. 3/2*b* draw the centre line ABCD, and mark a point where this cuts one of the first waves. B is a corresponding oint say four complete waves to the right, while C and D e respectively eight and twelve waves to the right.

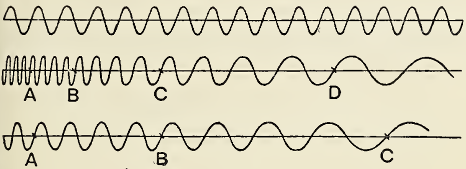


Fig. 3/2

Now the spring makes its vibrations *in equal times* (like a endulum). Thus the trolley has moved through the distances B, BC, and CD in equal intervals of time (namely, the time ccupied by four vibrations of the spring). Measure AB, C, and CD. In an actual experiment these were found to e 1·59 in., 2·98 in., and 4·37 in. We notice that 2·98 – ·59 = 1·39, and that 4·37 – 2·98 = 1·39. Thus in the econd interval (of four vibrations) the trolley travelled 1·39 . farther than it did in the first, and in the third interval it avelled 1·39 in. farther than it did in the second. Apparently [2]

[1] As the trolley is accelerating the tension in the string is actually little less than 10 gm. (cf. Ex. 3 on p. 34). The difference, however, too slight to make any practical difference to the experimental results.

[2] I.e. as far as our measurements go; but the fact that we get 1·39 vice over might be due to coincidence. By making a greater number f measurements we can show that the acceleration really *is* uniform, nd incidentally this establishes the important point that if a given iass is in motion under the action of a constant force, its acceleration ill be uniform.

the acceleration is uniform, and we may represent it by t number 1·39.[1]

We now treat Fig. 3/2*c* in the same way (the porti beyond C is not completed in the figure). The accelerati turns out to be 2·78, which is just twice 1·39. Thus doubling the applied force we have also doubled the acceler tion. We may try other applied forces, e.g. 25 gm., 30 g etc., and make a graph in which applied force (F) is plott against acceleration (a). It will be found that a strai line is obtained, showing that *the acceleration is proportio to the applied force.*

So much for question (i), in which we altered the fo but kept the mass constant. Let us now consider questi (ii), in which we alter the mass but keep the force constant.

As already mentioned, there are four heavy steel cylind of similar shape and size, built into the trolley, and by taki out one or more of these we can readily alter the mass. F instance, suppose the trolley weighs 1600 gm., and that ea of the cylinders weighs 400 gm. By experiments simi to that already described, we find the acceleration *using constant moving force* (say 15 gm.) for (i) trolley alone, 16 gm., (ii) trolley + one cylinder, total 2000 gm., (iii) trolley two cylinders, total 2400 gm. and so on, up to trolley + f cylinders, total 3200 gm.

(N.B. With each increase in the load, the friction w increase. We correct this source of error by slightly incre ing the weight in the box, and then adjusting the slope, that the trolley shall move with uniform velocity. T adjustment must be made for each of the loads with whi we experiment.)

On working out our results we find that *the accelerati is inversely proportional to the weight of the trolley* (includi from none to four cylinders).

Now, it cannot really be the *weight* of the trolley that affecting the acceleration, for the weight acts vertica

[1] 1·39 is not the actual acceleration, which would be velocity ad per *second*, while 1·39 is the velocity added in the time occupied 4 vibrations—not necessarily a second. Still, for comparative p poses the time occupied by 4 vibrations will serve us just as well 1 sec., so long as we stick to this same unit of time throughout.

wnwards, and so could not affect movement in a horizontal ection. But if the quantity concerned is not weight, it ist be something proportional to weight. This something is *iss*. Hence we conclude that *for a constant moving force, the celeration is inversely proportional to the mass moved*, or

$$mass \times acceleration = a\ constant.$$

Mathematical Expression. We have seen that (i) when the iss is constant, *acceleration* $\propto$ *applied force*, and (ii) when e force is constant, *mass* $\times$ *acceleration* is constant. Both ese rules are included in the statement $F \propto ma$, where a the acceleration produced in a body of mass m by a force F. It is important to notice that ma is equal to the *rate of inge of momentum*. For suppose a body of mass m has elocity u, which in the course of a very short time t changes v. The momentum of the body has changed from mu to , and as this has taken place in time t, the rate of change of

omentum is $\dfrac{mv - mu}{t}$

$$= m \times \frac{v - u}{t}$$
$$= m \times \text{(rate of change of velocity)}$$
$$= m \times \text{acceleration}$$
$$= ma.$$

Thus $F \propto ma$ or $ma \propto F$ is equivalent to saying that the te of change of momentum is proportional to the applied rce. This is Newton's *Second Law of Motion*, which may be rmally stated thus: *Rate of change of momentum is propor-nal to the applied force, and takes place in the direction in iich that force acts.*

Absolute Unit of Force. It is shown in mathematics that $F \propto ma$, then $F = kma$, where k is some constant. Now, we define our unit of force as that force which, when acting on unit mass, causes it to move with unit acceleration, have F, m and a all $= 1$ in our equation, which then comes $1 = k \times 1 \times 1$. Thus $k = 1$, and our equation w reads $F = ma$. This equation is of great importance, d is often referred to as the *fundamental kinetic equation*. otice that it holds good only when the unit of force is defined the way just stated.

Impulse of a Force. We can express Newton's second l in such a way as to bring out more clearly the questio *time*. For as we saw on the preceding page, $\frac{mv - mu}{t} =$ and $ma = F$,

$$\therefore \quad F = \frac{mv - mu}{t}, \quad \text{or} \quad Ft = mv - mu.$$

Thus the change of momentum, $mv - mu$, produced i body of mass m by a force F acting for time t, is equal to This product (*force*) $\times$ (*time*) is known as the ***impulse the force.***

It often happens that a body of considerable mass has velocity very rapidly reduced. When we hit a nail wit hammer, for instance, the velocity, u, is very quickly brou to zero. Hence $Ft = mv - mu = 0 - mu = -mu$ (minus sign indicating that while the original velocity downward, the change in velocity is upward). As m is c siderable, so also is Ft. But t is very small, and therefor is very large. Thus great force is brought to bear upon nail.

When making a catch at cricket, a player experiences t impulse Ft. By drawing back his hands as the ball reac him, he greatly increases t and correspondingly reduces F.

Absolute unit and gravitational unit. In previous work have very often used another unit of force—the pound wei This is called a *gravitational* unit, because its magnit depends on the force of gravity. For instance, in Chapte of our earlier book we saw that 1 lb. wt.—the force w which a mass of 1 lb. is attracted to the earth—is sligh greater at the north pole than at the equator.

On the other hand, our absolute unit is quite independ of gravity. Imagine a smooth horizontal table in which a long straight groove. In the groove there rests a smo platinum ball whose mass is 1 lb. (i.e. there is the same amo of platinum in it as in the standard pound). To this m we now apply a steady push, enough to make it move w an acceleration of 1 foot per sec. per sec. This steady p is, of course, our *absolute* unit, commonly known as

poundal. Because the movement is horizontal, the force required is quite independent of gravity. If it were possible to carry out our 'horizontal table' experiment on the surface of the moon (where the force of gravity is only about $\frac{1}{6}$th of what it is on the earth), the force required to produce unit acceleration would still be exactly the same. 'Absolute' means 'loosed from'—loosed or released from any dependence on the force of gravity.

Relation between the two units. When a mass of 1 lb. is falling freely, it is being pulled down by its own weight—1 lb. wt.—and this force causes it to move with an acceleration of g ft. per sec. per sec. (where g = about 32). Hence we may write

poundal acting on a mass of 1 lb. makes it move with acceleration 1

but

lb. wt. acting on a mass of 1 lb., makes it move with acceleration g.

$\therefore$ 1 lb. wt. $= g$ poundals.

$$\text{r 1 poundal} = 1/g \text{ lb. wt.}$$
$$= \tfrac{1}{32} \text{ ,, ,, (approx.)}$$
$$= \tfrac{1}{2} \text{ oz. weight approx.}$$

The dyne. In the c.g.s. system our unit of mass is not 1 lb., but 1 gm., and our unit of acceleration is an acceleration of 1 centimetre (not 1 ft.) per sec.^{2}

Thus the absolute unit of force in this system is *that force which when acting upon a mass of* 1 *gm. causes it to move with an acceleration of* 1 *centimetre per second per second.* This unit of force is known as the ***dyne.***

Just as 1 poundal $= 1/g$ lb. wt., so 1 dyne $= 1/g$ gm. wt. Notice, however, that while in the first case g = approx. 32 ft. per sec. per sec.) in the second case g = approx. 981 cm. per sec. per sec). Thus 1 dyne $= 1/981$ gm. wt., and so it is approximately equal to the weight of 1 milligram.

We will now consider some numerical examples relating to the subject matter of the preceding pages.

Example 1. *A constant force of* 2 *lb. wt. acting on a mass o* 20 *lb. gives it a velocity of* 12·8 *ft. per sec. How long has the forc acted?* $(g = 32)$.

Taking the kinetic equation $F = ma$, F must be expressed i poundals.

Thus $F = 2$ lb. wt. $= 64$ poundals.

$m = 20$ lb.

$\therefore\ 64 = 20a.$

$\therefore\ a = 64 \div 20 = 3{\cdot}2$ ft./sec.^{2}

To acquire velocity of 3·2 ft./sec. it takes 1 sec.

$\therefore$ „ „ „ 12·8 „ „ $1 \times \dfrac{12{\cdot}8}{3{\cdot}2} = \mathbf{4\ sec.}$

Example 2. *A train of* 100 *tons acquires a velocity of* 40 *m.p.h in the same time that another train of* 150 *tons acquires a velocit of* 60 *m.p.h. Compare the forces exerted by the engines.*

Taking 1 ton as our unit of mass and 1 m.p.h. as our unit o velocity we have

momentum acquired by first train $= 100 \times 40 = 4000$ units, an
momentum acquired by second train $= 150 \times 60 = 9000$ units.

These momenta have been acquired in equal time.

$$\therefore \frac{\text{rate at which 1st train has been acquiring momentum}}{\text{rate at which 2nd train has been acquiring momentum}} = \frac{4000}{9000} = $$

But by Newton's Second Law, these rates are proportional t the forces.

$\therefore$ the two forces are in the ratio **4 : 9**.

Example 3. *A mass of* 8 *lb. resting on a smooth table is attache by fine thread to a weight of* 2 *oz. which hangs over the edge. Fin* (a) *the pull in the string and* (b) *the acceleration with which th weights move.*

Total mass moved $= 8\frac{1}{8}$ lb.

Moving force $= 2$ oz. weight $= 4$ poundals.

$\therefore$ in equation $F = ma$

we have $F = 4$ and $m = 8\frac{1}{8}$

$\therefore\ a = F \div m = 4 \div 8\frac{1}{8}$

$= \mathbf{0{\cdot}492\ ft./sec.^2}$

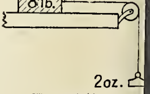


FIG. 3/3

Now consider the 8 lb. mass. Its acceleration has just been found ($= 0{\cdot}492$ ft./sec.^{2}). Thus in equatio

$F = ma$

we have $F = 8 \times 0{\cdot}492$

$= \mathbf{3{\cdot}94\ poundals,}$

which is the tension in the string.

Example 4. *With good brakes, a motor-car travelling at* 30 *m.p.h.* *n be brought to rest in a distance of* 30 *ft. Show that the total* *sistance to its motion must be approximately equal to its own weight* *ake* $g = 32{\cdot}2$).

Let us first find the acceleration (negative).

30 m.p.h. = 44 ft./sec.

$$\therefore u = 44. \quad v = 0. \quad s = 30. \quad a = ?$$

From $v^2 = u^2 + 2as$

we have $0 = 44^2 + 60a$.

$$\therefore a = -\frac{484}{15} \text{ ft./sec.}^2$$

Suppose the car weighs m lb.

Then from $F = ma$, we have force resisting motion $= m \times \dfrac{484}{15}$ poundals.

$$= \frac{m \times 484}{15 \times 32{\cdot}2} \text{ lb.wt.}$$

$$= 1{\cdot}002\, m \text{ lb.wt.}$$

Thus the force resisting motion is almost exactly equal to lb., the weight of the car.

Questions

1. Describe Fletcher's Trolley, and explain how you would e it to test the statement 'force is proportional to mass × ac- eration.'

The lengths of six successive individual waves on a Fletcher's olley trace are 3·2 cm., 3·5 cm., 3·8 cm., 4·1 cm., 4·4 cm., and ' cm. The period of the vibrator is one-fifth of a second. nd (a) the acceleration of the trolley, and (b) the average velocity er the whole period covered by these readings. *Oxf.*

2. State Newton's second law of motion, and show how it can used to define a unit of force.

A balloon and contents of total mass 2000 lb. are falling freely h an acceleration of 2 ft. per sec.² Find the change in the tical motion after 125 lb. of ballast have been thrown out. glect air friction and take $g = 32$ ft. per sec.² *O.C.*

3. A barrel weighing 100 lb. is being pulled up a smooth plane lined at 30° to the horizontal by means of a rope which is rallel to the surface of the plane. If the tension in the rope 130 lb. wt., what is the acceleration of the barrel? *O.C.*

4. A train of mass 200 tons travels at 60 m.p.h. The brakes suddenly applied, producing a retarding force equal to one- th the weight of the train. Find the distance the train runs a level track before coming to rest. *O.C.*

CHAPTER 4

NEWTON'S THIRD LAW OF MOTION

If a man presses his thumb against a table, the table presse with an equal force against his thumb—otherwise his thum would go through the table. If a load is attached to a sprin balance and exerts a downward force of 3 lb. wt. on th spring, the spring exerts an upward force of 3 lb. wt. on th load. A magnet attracts a piece of iron with a certain forc (not necessarily enough to make it move). The iron attract the magnet with an equal force, but in the opposite directio

The cases just noted, and thousands of others (a few o which we will consider presently), are summed up in Newton' ***Third Law of Motion.*** This states that *to every action ther is an equal and opposite reaction.*

From the examples given, it might be thought that th law applies only to bodies at rest, but this is by no mean the case. Let us see how it applies to the very common ac of walking. Here the force which gives us our 'action an reaction' is *friction,* this being the force which prevents on surface from sliding over another (or tends to prevent it When a man is walking, his foot pushes backwards again the ground, and the ground pushes forward against his foo It is the action of this forward force on the man's body th causes him to advance. On a smooth surface such as ice th frictional forces just mentioned are small, and the man fin it difficult to move forward.

Sledge. Horse and Cart. If a man is pulling a sled forward with a force T_1 (Fig. 4/1), the sledge is pulling hi backwards with an equal force T How, then, is it possible for any a vance to be made?

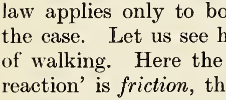


Fig. 4/1

Let us think of the man-plus-sled as a *whole.* Suppose the force friction called into play, as the ma braces his feet against the groun is F_1. He pushes backward with a force F_1, but probab the only effect is to disturb a little snow. The importa

int is that the ground pushes the man forward with a rce F_1.

Suppose that when the sledge begins to move, it has to ercome a frictional force F_2. Then if F_1 is greater than F_2 e man-plus-sledge will advance under the action of a sultant forward force $F_1 - F_2$. When we come to the ore detailed study of friction (Chapter 9), we shall see at F_2 cannot be greater than F_1, but it may become equal it. In that case $F_1 - F_2 = 0$, and the man cannot move e sledge. It will be seen that T_1 and T_2 are internal forces, d we are not really concerned with them any more than are with the internal forces which hold the various parts the sledge together.

The case of a horse pulling a cart is very similar. F_1 presents the total frictional forces between the horse's feet d the ground, and F_2 the 'rolling' frictional forces between e two wheels and the ground. The tension in the traces nsists of internal forces represented by T_1, T_2 ($T_1 = T_2$, t acts in the opposite direction).

When considering matters such as walking, a horse pulling cart, etc., we pay little attention to the backward push of e man's feet (or horse's hoofs) on the earth, because the ter is much too big to be moved appreciably. Often, wever, this backward force is exerted against an object only moderate size, and then we may have to consider w this object is affected. We have a good example in the e of a shot fired from a gun.

Recoil of a gun. Suppose M and m are the masses of gun d bullet respectively. Each is acted on by the explosive ce for the same time t. At the end of this time, suppose gun has acquired a velocity V and the bullet a velocity v. idently the gun has acquired a momentum MV and the llet a momentum mv. The *rates* of change of momentum

$\frac{MV}{t}$ and $\frac{mv}{t}$ respectively, t being the same for each.

But as the forces acting on gun and bullet are exactly ual (Newton's third law), the rates of change of momentum the latter are also equal (second law), i.e. $MV/t = mv/t$. $MV = mv$.

Thus the two bodies subject to the action and reaction acquir equal momenta (in opposite directions). This result applie not only to the particular case discussed—that of the gu and bullet—but also to all cases of action and reaction.

If $MV = mv$, it follows that $M/m = v/V$. Thus we hav a means of comparing two masses. Let them 'act and react upon one another, and note the velocity acquired by each The respective masses are in the inverse ratio of these velocitie

Conversely—and this is of much more practical interest— if we know the ratio of the masses, we can calculate that o the velocities. Let us consider an example.

Example 1. *A military rifle weighing* 9 *lb. fires a bullet weighin* 1 *oz. with a muzzle velocity of* 2000 *ft./sec. With what velocity wi the gun begin to recoil?*

Let required velocity $= V$ ft./sec.
Then momentum acquired by gun $= 9 \times V$ f.p.s. units.

and momentum acquired by bullet $= \frac{1}{16} \times 2000$ f.p.s. units.

Equating, we have $9V = \frac{2000}{16}$

$$\therefore V = \frac{2000}{16 \times 9} = \mathbf{14\ ft./sec.}\ \text{approx.}$$

Similar cases. In a Catherine wheel the 'gun' is free t move in a circular direction, and the effect is too well know to need description. If a man in a boat A is pushing anoth boat B with an oar, A (if free to move) acquires a momentu equal to that of B, but in the opposite direction. If A is barge and B a small rowing-boat, the velocity of A may b too small to be perceptible, though its momentum will sti be equal to that of B.

Suppose you are standing on a plank that bridges a sma stream, and you jump into the air, the effect on the plank obvious enough—it acquires a downward momentum equ to your own momentum upwards. If when you make you upward jump you are standing on solid ground, it is still tru that the earth acquires an equal downward momentum However, taking your own weight as 1 cwt., and that of th earth as 6×10^{21} tons, it is evident that the velocity acquir by the earth will be of no very disturbing character.

Questions

1. State Newton's Laws of Motion.

A wooden block, of mass 5 lb., is pulled along a rough horizontal ıble by means of a string parallel to the surface of the table, hich passes over a light, frictionless pulley at the edge of the ble and carries a weight of 3 lb. The resistance offered by the ırface of the table to the motion of the block is 2 lb. wt. Calculate ıe acceleration with which the block moves. ($g = 32$ ft./sec.^{2}, *Oxf.*

2. State the principle of *conservation of momentum* and show ow it follows from Newton's laws of motion.

If a force of 10 lb. wt. acts steadily on a mass of 1 ton, how ng will elapse before the mass has moved 14 ft. if it starts from st? *O.C.*

3. A spring balance in a lift supports a body of mass m grams. escribe and account for any changes which occur in the spring lance reading (a) when the lift is rising or falling with uniform locity, (b) when falling with uniform acceleration, (c) when ing with uniform acceleration. *Dur.*

4. 'To every action there is an equal and opposite retion.' What is meant by this statement? Use it to explain e changes in the horizontal motion of a dinghy when a man in e bows walks to the stern, stands motionless, and then dives the water.

A dinghy, originally at rest, is pulled for 3 sec. with a steady rce of 25 lb. weight. Calculate its velocity at the end of this ne and the work done in pulling it, assuming the water retance to be negligible. (Mass of dinghy = 600 lb., $g = 32$ ft. r sec. per sec.) *J.M.B.*

5. Define (a) velocity, (b) momentum of a moving body. hat is the relationship between the force applied to a moving dy and the momentum which it imparts to the body?

A force P acts for t seconds on a body of mass m, which is at st, and gives it a velocity v. The same force P then acts for T conds on another body of mass M at rest and gives it a velocity Find the ratio m/M in terms of t, v, T and V.

Distinguish between the mass of a body and its weight. *Camb.*

CHAPTER 5

WORK, ENERGY AND POWER

We have more than once had occasion to recall the definitio of Force as 'that which changes or tends to change the stat of rest or motion of a body.' Now, when a force merel *tends* to change a body's state of rest, it may be very useles from a practical point of view. A furniture remover wh found that one of his men had been pushing and pulling at grand piano for half an hour, without moving it an inch would be more likely to dismiss him for stupidity than t commend him for perseverance. 'Force is all very well,' h would say, 'but only when it produces movement.'

Force when it produces movement is said to *do work* Examples abound on every hand—a horse pulling a car steam driving a piston, an electromagnet picking up scra iron, and so on.

Sometimes movement takes place in a direction opposit to that in which the force is acting. A horse beginning to pu a load up a hill may find himself dragged backwards, especiall if the ground be slippery. In such a case the work done b the horse is negative, but we usually say that work is don 'against the force.' If you lift a book or a chair, you do wor against the force of gravity.

We shall now have no difficulty in understanding a form definition.—*A force is said to do* ***work*** *when it produces mov ment in the direction of its line of action; if movement tak place in the opposite direction, work is said to be done again the force.*

We must now consider how work can be measured, i. we must fix upon a unit. Evidently this will have to tak into account (i) the force itself, (ii) the distance through whic it has caused movement to take place. One very comm unit is the ***foot-pound***, which is *the work done when a for of* 1 *lb. wt. moves its point of application through a distance* 1 *ft.* We do 1 ft.lb. of work when we raise a pound weig through a vertical height of 1 ft. If we raise it 3 ft., we

ft.lb. To raise a 5 lb. weight through a vertical height of ft. we have to do $5 \times 4 = 20$ ft.lb. and so on.

Of course the direction in which work is done is by no means ways vertical. Suppose the 5 lb. weight just mentioned ere being dragged along a table, and the dragging force quired were 2 lb. wt., then the work done in dragging the eight 4 ft. would be $2 \times 4 = 8$ ft.lb. In this case the work done against the force of friction.

Example 1. *A labourer weighing* 10 *stones carries a pile of slates eighing* 50 *lb. to the top of a house* 30 *ft. high. Find* (i) *the total ork done, and* (ii) *the useful work.*

$$\begin{aligned} \text{Weight of man} &= 10 \text{ stones} = 140 \text{ lb.} \\ \text{,, \quad ,, slates} &= \phantom{10 \text{ stones} =\ } 50 \text{ lb.} \\ \text{Total weight} &= \phantom{10 \text{ stones} =\ } 190 \text{ lb.} \\ \therefore \text{ total work} &= 190 \times 30 = \mathbf{5700\ ft.lb.} \end{aligned}$$

The only *useful* work is that done in lifting the slates,
. useful work $= 50 \times 30 =$ **1500 ft.lb.**

Other units of work. The foot-pound is of course a *gravitation* it, and as the pound-weight varies slightly from place to ace the foot-pound varies correspondingly.

An *absolute* unit of work would be the **foot-poundal**—the ork done when a force of 1 poundal moves its point of plication through a distance of 1 ft. The foot-poundal $= \frac{1}{g}$ lb., where $g =$ approx. 32 (ft. per sec. per sec.).

In the c.g.s. system we have as a gravitation unit the **ntimetre-gram,** a term which explains itself. The corre- onding absolute unit would be the work done when a force of dyne (p. 33) moves its point of application through a stance of 1 centimetre. This unit is known as the *erg*.

The erg $= \frac{1}{g}$ centimetre-grams, where $g =$ approx. 981 n. per sec. per sec.). Thus the erg would be roughly equal the work required to lift a milligram weight through a rtical height of 1 cm. This unit is so very small that we en use the **joule** as our absolute unit, the joule being equal 10^7 ergs.

Power. If a man is buying a machine to do work—perhaps pump to raise water from a mine, or a crane to raise blocks

of stone, etc., during building operations—he does not ask how much work the machine can do, but the *rate* at which it can do it. Rate of working is known as *power*.

The obvious unit of power seems to be a rate of working of 1 ft.lb. per second. For practical purposes, however, this is much too small, and a unit known as the ***horse-power*** is employed, this being *a rate of working of 550 ft.lb. per second.*

This unit is due to the famous engineer James Watt. He arranged to have a barge pulled along a canal by a good dray-horse, a strong spring-balance being fixed in the tow-rope. He multiplied the force in pounds weight by the speed of the horse in feet per second, and so obtained the number of foot-pounds done per second. After making certain corrections he came to the conclusion that a horse can work at the rate of 550 ft.lb per second. Actually, an average horse cannot maintain this rate of working for any very long period.

Example 2. *A man weighing* 180 *lb. bounds up a flight of stairs* (12 *steps each* 8 *in. high*) *in* 3 *sec. At what horse-power is he working?*

Total height $= 12 \times 8$ ins. $= 8$ ft.

Work done in lifting his own weight (180 lb.) through a vertical height of 8 ft. $= 180 \times 8$ ft.lb.

He does this in 3 sec.

$$\therefore \text{ work done per sec.} = \frac{180 \times 8}{3} \text{ ft.lb.}$$

$$\therefore \text{ H.P.} = \frac{180 \times 8}{3 \times 550} = \mathbf{0{\cdot}87.}$$

(N.B. Of course a man could work at this rate only for a very short time.)

Example 3. *'The mean flow of the Niagara river is about* 222,000 *cub. ft. per second with a fall of* 160 *ft.' Encyc. Brit.*

Calculate the available horse-power (1 *cub. ft. of water* $= 62{\cdot}4$ *lb*

Water falling per sec. $= 222{,}000 \times 62{\cdot}4$ lb.

Fall $= 160$ ft.

$\therefore$ Work done per sec. $= 222{,}000 \times 62{\cdot}4 \times 160$ ft.lb.

$$\therefore \text{ H.P.} = \frac{222{,}000 \times 62{\cdot}4 \times 160}{550}$$

$$= \mathbf{4{,}030{,}000} \text{ approx.}$$

In the examples just given the work has been done by, or against, gravity, and such cases are commonly met with in daily life. Even commoner, however, are cases in whi

ork is done against friction. Think, for instance, of the work one by a horse pulling a plough, or by a man cycling on a vel road.

Example 4. *A train weighing* 100 *tons travels on the level at a niform speed of* 45 *m.p.h. The frictional resistances are equivalent* 10 *lb. weight per ton. Find the H.P. at which the engine is orking.*

The frictional resistances are equal to a backward force of) $\times$ 100 = 1000 lb.wt.

Now since the train is moving with uniform velocity, the *sultant* force on it is zero (by Newton's second law). Therefore e engine must be exerting a forward pull of 1000 lb.wt. to ılance the frictional forces.

$$45 \text{ m.p.h.} = 66 \text{ ft. per sec.}$$

$$\therefore \text{ work done per sec.} = 1000 \times 66 \text{ ft.lb.}$$

$$\therefore \text{ H.P.} = \frac{1000 \times 66}{550} = \mathbf{120.}$$

Energy. An energetic man is one who habitually does a eat deal of work. If he is merely *capable* of doing work, ıt does not do it, we describe him not as energetic, but as zy.

In science, however, a body is said to possess energy if it *capable* of doing work. Moving air (i.e. wind) possesses ergy, for it is capable of driving a ship along, or turning a ndmill. A shell fired from a gun can do the (destructive) ›rk of knocking down a bridge or a house. When a grand- ther clock has just been wound up, the weights possess ergy, because as they slowly descend they will do the work moving the various parts of the clock. If we stop the ›ck, we still say that the weights possess energy, because ey are *capable* of doing work though they are not actually ing it.

When we examine more closely the cases we have just oted, we see that they are of two different kinds. The ›ving air and the shell are capable of doing work because ey are *moving*; the weights of the clock are capable of doing rk because of their high *position*. These two kinds of ergy are known respectively as *kinetic* and *potential*, i.e. *ody possesses* ***kinetic energy*** *when it is capable of doing work account of its motion; it possesses* ***potential energy*** *when s capable of doing work on account of its position.*

Potential energy may be turned into kinetic, and vic versa. Of this we have a good example in the swinging a pendulum. Suppose the bob is at A on the extreme lef of its path (Fig. 5/1). It is in its highest position and ca do work as it descends the path AV, i.e. it has potential energy On the other hand, it is for a moment stationary while in th position A, and so possesses no kinetic energy.

Now let the bob swing into the position V. It has the reached its lowest point, and so has lost all its potential energy. But it has attained its maximum speed, and so its kinetic energy is at a maximum. In short, at A potential energy but no kinetic; at V kinetic energy but no potential. The one kind has given place to the other. As the bob ascends the arc VB, its kinetic energy will decrease, sinking to zero at B, where its potential energy will once more have reached a maximum.

FIG. 5/1

This conversion of one kind of energy into the other is also seen in the case of the pile-driver. Here a heavy iron block is hauled up to a positio near the top of a high tower of scaffolding, i.e. potenti energy is imparted to it. It is then allowed to fall, acqui ing kinetic energy as it does so, and this kinetic energy made to do the useful work of driving in the piles. Th processes of hauling up and then releasing are of cour repeated as often as required.

Measurement of energy. As the energy of a body is its capacity for doing work, we naturally measure this energy by the work the body is capable of doing —in foot-pounds or foot-poundals, for instance. Thus if the 'weight' of a grandfather clock has a mass of 8 lb. and has been raised to a height of 3 ft., its potential energy is $8 \times 3 = 24$ ft.lb. For imagine this mass A to be attached to another equal mass B by a thread passing over a pulley. Then if there were no friction or air resistance, A, in falling 3 ft., would be just able to raise B 3 ft., i.e. the work it is capable of doing—its energy—is 24 ft.lb. 24 g ft.pdls. Speaking generally, we see that if a mass

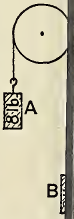


FIG. 5/

ı lb. is at a height of h ft. above the lowest position it can ccupy, then its potential energy is mh ft.lb., or $mh \times g$ .pdls.

So much for potential energy. With regard to kinetic ıergy, it can be proved that the kinetic energy possessed by body of mass m moving with velocity u, is equal to $\frac{1}{2} mu^2$.

For suppose the body is brought to rest by a force F, after avelling a distance s. Let a be the acceleration (negative). Applying the formula $v^2 = u^2 + 2as$ we have $v = 0$, so ıat $0 = u^2 + 2as$.

$$\therefore a = -\frac{u^2}{2s}.$$

he work done *by* the force F, acting through a distance $s = Fs$.

But $F = ma$ (p. 31).

$$\therefore \text{ work done by force } F = mas$$
$$= m \times \frac{-u^2}{2s} \times s$$
$$= -\tfrac{1}{2} mu^2.$$

kinetic energy of moving body

$= $ work done *against* force F in process of coming to rest

$= -(-\frac{1}{2} mu^2) = \frac{1}{2}$ **mu²**.

Example 5. *What is the kinetic energy of a mass of* 6 *lb. moving th a velocity of* 10 *ft. per sec.?*

$$\text{Required K.E.} = \tfrac{1}{2} mu^2$$
$$= \tfrac{1}{2} \times 6 \times 10^2$$
$$= \mathbf{300\ ft.pdls.}$$

Energy and Momentum. We must take care not to confuse ese two terms. We have just seen that the kinetic energy of mass m moving with velocity u is $\frac{1}{2}mu^2$, while its momentum equal to mu (p. 27).

Notice that if the velocity of a body is trebled, its momentum also trebled, but its energy is increased nine-fold. Similarly, course, for other numbers. Thus we should expect a body oving with very high velocity to be remarkable for its energy ther than for its momentum.

This is clearly seen in the example overleaf.

Example 6. *A military rifle weighing* 9 *lb. fires a bullet weighin* 1 *oz. with a muzzle velocity of* 2000 *ft./sec. Find* (*i*) *the momentum* (ii) *the energy of both gun and bullet just after the shot is fired.*

This example was studied on p. 38 from the point of vie of momentum. There it was shown that the momentum of th bullet is equal to $\frac{1}{16} \times 2000$ or 125 f.p.s. units; and it follow from Newton's 2nd and 3rd laws that the momentum of the gu is equal and opposite to this.

It was also shown that the gun begins to recoil with a velocit of 14 ft./sec.

$$\therefore \text{ K.E. of gun} = \tfrac{1}{2}mv^2 = \frac{1}{2} \times 9 \times 14^2 = 882 \text{ ft.pdls.}$$

$$\text{But K.E. of bullet} = \frac{1}{2} \times \frac{1}{16} \times 2000^2$$

$$= 125{,}000 \text{ ft.pdls.}$$

Thus the kinetic energy of the bullet is enormously great than that of the gun, though the two have equal momenta.

Equivalence of P.E. and K.E. On p. 44 we considere examples in which a loss of potential energy is accompani by a gain in kinetic energy, and vice versa. This at on suggests the question, 'when a body loses potential energy, do it gain *an equivalent amount* of kinetic energy, and vice versa?

The following example will throw much light on the questio

Example 7. *A body of mass* 10 *lb. is raised to a vertical heig of* 80 *ft. Find the total of its P.E. and K.E.* (i) *at this height,* (i *after it has fallen* 40 *ft.*, (iii) *after it has fallen to ground level.*

(i) Before being allowed to fall its P.E. $= 10 \times 80 = 800$ ft.l or $800 \times 32 = 25{,}600$ ft.pdls.

K.E. $= 0$

$\therefore$ P.E. + K.E. = **25,600 ft.pdls.**

(ii) After falling 40 ft. its P.E. is halved and is $\therefore$ 12,800 ft.pd

To find its K.E. we must first calculate its velocity. We ha $u = 0$, $s = 40$, $a = 32$, $v = ?$

Applying the equation $v^2 = u^2 + 2as$ this gives $v^2 = 0 + 2$ $32 \times 40 = 2560$.

$$\therefore \text{ K.E.} = \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 10 \times 2560$$

$$= 12{,}800 \text{ ft.pdls.}$$

$$\therefore \text{ P.E. + K.E.} = 12{,}800 + 12{,}800$$

$$= \mathbf{25{,}600 \text{ ft.pdls.}}$$

(iii) After falling to ground level, P.E. = 0.

To find its velocity, we have $u = 0$, $s = 80$, $a = 32$, $v = ?$

$\therefore$ from $v^2 = u^2 + 2as$

we get $v^2 = 0 + 2 \times 32 \times 80$

$= 5120$

$\therefore$ K.E. $= \frac{1}{2}mv^2 = \frac{1}{2} \times 10 \times 5120$

$= 25{,}600$ ft.pdls.

$\therefore$ P.E. + K.E. = **25,600 ft.pdls.**

Thus we see that the *combined* P.E. and K.E. of the body the same in all three cases, and it can easily be shown that would be the same in any other position. As it falls, it ses potential energy, but gains *an equal amount* of kinetic ergy.

The foregoing is, of course, only a particular example of general case. The latter is not at all difficult to prove, t here we will content ourselves with merely stating it.— a body of mass m falls from a height h, the sum of its P.E. d K.E. is constant and equal to mgh.

It is assumed in this statement that the resistance of the may be neglected. In practice, some air is set in motion the body falls, and a more exact statement would be that s of P.E. of falling body = gain of K.E. of body *plus* gain K.E. of air.

It can be shown that the same principle holds good for a dy running down a slope, i.e. loss of P.E. = gain of K.E. this statement we are neglecting not only the resistance the air, but the frictional resistance of the surface of the pe.

Conservation of energy. We have seen that as a body falls loses its potential energy and acquires a corresponding ount of kinetic energy. But what happens when it reaches ground? It has lost all its potential energy, and as it nes to a stop it has presumably lost all its kinetic energy .

We can get an idea of what really happens if we let our

'falling body' consist of a closed picnic-basket packed wit crockery. This has unfortunately slipped over the vertic edge of a quarry.

On striking the ground the kinetic energy of the body *a a whole* disappears, but the constituent parts, the crocker at once begin to shake about—let us use the word *vibrate*— with great violence (with woeful results). We can trace wha has happened to some at least of the original kinetic energ It has been transferred from the whole to the constituen parts.

But suppose the falling body is of a more tightly packe character—a lead bullet, for instance? In this case th constituent parts are the molecules. There is good reaso to believe that these are always in a state of vibration, an when a moving bullet comes to a sudden stop, the rate vibration of the molecules is greatly increased. This increase rate of vibration makes itself felt as *heat*. Indeed, a bull that has just been brought to a sudden stop by striking a iron target is usually too hot to handle.

There are abundant examples of this conversion of kinet energy into heat. When a bicycle pump is worked it so becomes warm. A match rubbed against a rough surfa becomes hot enough to take fire. Saws, files, drills, a become hot in use; and so on.

Now, when considering potential and kinetic energy, w saw that one could be converted into an exact equivale of the other. It is tempting to enquire whether 'mechanic energy can be converted into an exact equivalent of heat.

Actually it can. It was discovered in 1847 by Dr. Jou of Manchester that 774 ft.lb. are equivalent to a unit of he now called the British Thermal Unit[1] as definitely as 12 pen are equivalent to a shilling. Are there still other forms energy? Is it possible that no energy is ever really lost created, though it may be turned from one form into anothe These are questions which we shall be better able to answ when we have made some progress in other branches Physics.

[1] I.e. the amount of heat required to raise the temperature of 1 of water 1 degree Fahrenheit.

Questions

A

1. How much work is done when

(i) a 7 lb. weight is lifted on to a table 3 ft. high,

(ii) a man weighing 10 stones climbs a ladder 12 ft. high,

(iii) a chair weighing 20 lb. is dragged 5 ft. across a floor, average frictional resistance being 3 lb.wt.?

2. Find the horse-power of a pump which every minute raises 5 galls. of water (1 gall. = 10 lb.) to a height of 40 ft.

3. In one hour a pump lifts 20,000 gallons of water 30 ft. bove the level of the surface of a reservoir. What horse-power s required for the pump? (1 gall. = 10 lb.).

4. Find

(i) the potential energy possessed by a clock weight of 3 lb. which has been raised to a height of 5 ft. above its lowest point.

(ii) the kinetic energy of a bullet weighing 1 oz. and travelling at the rate of 1000 ft. per sec.

In both cases express your answer in ft.pdls.

B

1. Calculate the two quantities *momentum* and *kinetic energy* or a body of mass 2 lb., dropped from height, (i) when it reaches he ground 81 ft. below, (ii) when it has reached halfway in its all. *C.W.B.*

2. What is meant by *force, work, power*?

A cyclist rides up a gradient of 1 in 44 (measured along the slope) t the rate of 6 miles per hour. If the total mass of man and nachine is 165 lb., calculate the horse-power he is developing. Vhy would your calculated value of the horse-power be lower han the real horse-power necessary? (1 H.P. = 33,000 ft.lb. vt. per minute). *Lond.*

3. A man weighing 12 stones runs up a flight of steps and in 0 sec. is 40 ft. above ground level. How much work does he lo and at what average rate in horse-power is he working? *Dur.*

4. Explain the terms 1 lb.wt., 1 dyne, 1 ft.lb., a horse-power. Vhat force acting along a smooth plane inclined at 45° to the iorizontal will keep a mass of 10 lb. on the plane in equilibrium?

A cyclist rides at 12 m.p.h. along a level road. If he expends nergy at the rate of 0·1 horse-power, what is the average value of the frictional forces? *Lond.*

5. If a pressure of 25 lb.wt. per sq. in. acts on the circular piston (radius 10 in.) of a steam engine, and drives the piston hrough a distance of 5 ft., find the work done in ft.lb. weight. *Camb.**

6. A train and its engine, weighing together 200 tons, are kep moving on a level track at 40 m.p.h. If the resistance to motio is 30 lb. per ton, what horse-power is being developed by th engine? *Camb.**

7. Define the terms *momentum, kinetic energy.*

A motor-car weighing 1 ton is travelling at 30 m.p.h. Fin the average force which must be exerted by the brakes to brin it to rest (*a*) in 11 sec., (*b*) in 44 yd. *Oxf.*

8. Describe any means by which a man who can exert a forc of not more than 220 lb.wt. can increase the potential energy o a body weighing 0·75 ton by 5000 ft.lb.

An aeroplane flying on a straight course at a height of 1000 ft has its engine switched off and glides down to an aerodrom Describe the changes in energy from the time of switching of till the plane comes to rest on the runway. *J.M.B.*

9. (*a*) Define (i) the *momentum* of a body, and (ii) its *kineti energy*. A body of mass 100 gm. falls freely from rest throug 490 cm. What is the gain in (*a*) kinetic energy, (*b*) momentum ($g = 980$ cm./sec./sec.)

(*b*) A shell fired horizontally from the muzzle of a gun break an electric circuit near the muzzle, so causing a plate to fal from rest. Simultaneously it makes a pointer trace a mark A on the plate. After travelling another 100 ft., the shell cause the pointer to trace another mark B on the falling plate, and i is found, by means of a microscope, that the distance AB is 1·51 in Find the average velocity with which the shell traverses thi 100 ft. (Take $g = 32·0$ ft./sec./sec.) *Camb.*

10. State Newton's second law of motion, and explain how th c.g.s. unit of force (the dyne) is derived.

Calculate the kinetic energy of a motor-car of mass 1 to moving at a speed of 30 m.p.h., stating the unit. What is th shortest distance in which the car can be stopped, (*a*) from 3 m.p.h., (*b*) from 60 m.p.h., if the maximum retarding force i equal to the weight of the car. *Camb.*

11. Describe a method of measuring the *acceleration due t gravity* (g).

A bullet weighing $\frac{1}{2}$ oz. is fired vertically upwards from th ground and reaches a height of 900 ft. Neglecting air resistance calculate (*a*) the initial velocity of the bullet, (*b*) the time tha elapses before the bullet reaches the ground again, (*c*) the energy (potential and kinetic) of the bullet at ground level, at the highes point reached, and half-way up. *C.W.B.*

12. State what you understand by *kinetic* and *potential energy* and give two examples of each. A body of mass 100 gm. fall from rest from a point 1000 cm. above the ground. Calculat the potential energy and the kinetic energy after it has bee falling for 1 sec.

Describe how the potential and kinetic energies change durin the swinging of a pendulum. *Dur.*

CHAPTER 6

MACHINES AND THEIR EFFICIENCY

Physics the word *machine*, is used in a rather special to indicate some contrivance for changing either the of application, the direction, or the magnitude of a More often than not our machine enables us to change three at once. Thus when a man is winding up a bucket water from a well, his force is applied at a point yards from the bucket itself. Again, while the direct force ed to lift the bucket would be an upward one, the man's ay actually be moving downwards. Lastly, the man ibly exerting a force considerably smaller than the of the bucket and water.

re certain to have some knowledge already of a number hines—the lever, wheel and axle, inclined plane and systems of pulleys—and you will have learnt how to the *force ratio* (or *mechanical advantage*) and *velocity* each case. In the present chapter we shall consider achines from a somewhat different point of view— that of the *work* we can obtain from them. At the me we shall seize the opportunity of making a fairly n revision of our previous work, with ns where necessary.

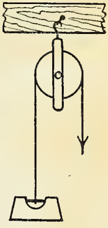


Fig. 6/1

ill begin by recalling some of the chief of pulleys.

s. In Fig. 6/1 we have the single fixed ey, in 6/2 a block and tackle (or 'single- ' system), and in 6/3 a 'separate-string'

s we shall almost immediately have occasion the terms 'force ratio' (or 'mechanical ge') and 'velocity ratio,' let us be sure remember their meaning.

The ***force ratio*** or ***mechanical advantage*** of a machine is

$$\frac{\textit{resistance overcome}}{\textit{effort applied}}$$

definition the 'resistance overcome' does not include

any resistance offered by the machine itself. Thus, referri to Fig. 6/2, suppose the block and tackle is being used raise a mass of iron L weighing 100 lb., and that the low block of pulleys weighs 18 lb. If the effort that has to applied at E is 30 lb., the force ratio is $\frac{100}{30} = 3\frac{1}{3}$, *not* $\frac{11}{3}$ because in the latter case we should be including a resistan offered by the machine itself.

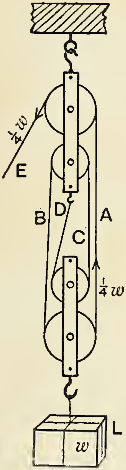


FIG. 6/2

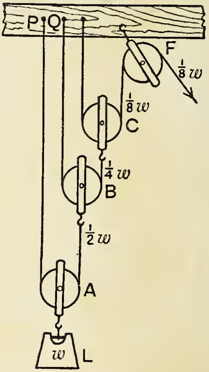


FIG. 6/3

The ***velocity ratio*** (or ***speed ratio***) of a machine is t ratio $\frac{\textit{distance through which effort acts}}{\textit{distance through which resistance is overcome}}$.

Again referring to Fig. 6/2, if we wanted to raise L 2 fe we should have to pull in 8 ft. of rope, i.e. E would have move 8 ft. Thus the velocity ratio would be $8 \div 2 = 4$.

We need not spend long over the single fixed pulley Fig. 6/1. If it were frictionless, the effort required to ra

given load would be practically equal to the load. Hence orce ratio = resistance ÷ effort = 1. In practice there is t least a little friction. Hence the effort must be greater han the resistance, and this makes the force ratio less than 1.

The velocity ratio is evidently 1, for to raise the load a ertain distance, the rope must be pulled through an equal istance.

In Fig. 6/2 suppose the load weighs w lb., and for the oment let us neglect the weight of the lower block, and also e resistance due to friction. The load is supported by our parallel cords, and the strain in each of these is therefore w. This would also be the effort required at E. Hence orce ratio $= w \div \frac{1}{4}w = 4$. In practice, the effort at E ould obviously be greater than $\frac{1}{4}w$, and so the force ratio ould be less than 4.

Now for the velocity ratio. Suppose we wish to raise L ft. To do this, each one of the four supporting cords must e shortened by 2 ft., and therefore the length of rope to be ulled in at E is $4 \times 2 = 8$ ft. Thus the velocity ratio is $\div 2 = 4$. Notice that neither friction nor the weight of e lower block makes any difference to the velocity ratio— raise L a certain distance we should still have to pull in our times that length of cord. On the other hand, the force tio is greatly affected by friction, and by the weight of the wer block.

Fig. 6/3 almost explains itself, but if it presents any ifficulty you should refer back to p. 43 of *Junior Physics*. ssuming frictionless and weightless pulleys, the force ratio ould be $w \div \frac{1}{8}w = 8$. Further, to raise L 1 ft., it can easily e shown that we should have to pull in 8 ft. of rope at F, nd so the velocity ratio is $8 \div 1 = 8$.

Still neglecting friction, let us work out the force ratio, upposing that L weighs 40 lb. and that each pulley weighs lb.

The two parts of the cord A are supporting a total weight f 44 lb., so the strain in each is 22 lb. The two parts of the ord round B are supporting this 22 lb. *plus* 4 lb. (the weight f B itself), total 26, so the strain in each is 13. Similarly, e strain in the next higher cord will be $\frac{1}{2}(13 + 4)$ or $8\frac{1}{2}$ lb., nd this will be the effort actually required. Thus the force

ratio will be $40 \div 8\frac{1}{2} = 4{\cdot}7$ (instead of the ideal 8 wi weightless pulleys). The velocity ratio however will still be

Efficiency. Principle of Work. It is evident that pulle and other machines, enable us to do *work*—a term defin on p. 40. In the case we have just been considering, if suppose L, weighing 40 lb., to have been raised 1 ft., o system of pulleys has enabled us to do work to the exte of $40 \times 1 = 40$ ft.lb.

But to obtain this result we have had to pull the cord F through a distance of 8 ft., the force applied being $8\frac{1}{2}$ l (see end of last paragraph). In this operation we have do work equal to $8 \times 8\frac{1}{2}$ or 68 ft.lb. We have, so to spea put 68 ft.lb. *into* our machine and have got only 40 ft.l *out* of it. The fraction $\frac{40}{68}$ is known as the *efficiency* of t machine in this particular case. We may say in general th the ***efficiency of a machine*** is the ratio $\dfrac{\textit{work got out of machin}}{\textit{work put into it}}$

Efficiency is often expressed as a percentage. In the ca just discussed it would be 59% ($= \frac{40}{68} \times 100$).

The efficiency of a machine may vary a great deal, accor ing to the load. In the case just considered L was tak as 40 lb., each pulley weighing 4 lb. Suppose L had be 80 lb. Then, working in the same way as on p. 53, easily find that the force required at F would be $13\frac{1}{2}$ lb. No suppose the 80 lb. load to be raised 1 ft.

$$\begin{aligned} &\text{Work got out of machine} &&= 80 \times 1 = 80 \text{ ft.lb.} \\ &\text{Work put into it} &&= 13\tfrac{1}{2} \times 8 = 108 \text{ ft.lb.} \\ &\therefore\ \text{efficiency} = \tfrac{80}{108} \times 100 = \text{(approx.) } 75\%. \end{aligned}$$

(With a load of 40 lb. we found that the efficiency was on 59%.)

There would be no great difficulty in verifying such resul by experiment. Thus we could hang a load of 40 lb. at and a scale-pan of known weight at F. In this pan we shou place weights until a point is reached at which the pan, released, will just move gently downwards.

We measure the distance of the load, and of the pan, abo the table or bench, and then allow the pan and its containe weights to fall as far as convenient, afterwards taki measurements again. We then have

(*load*) $\times$ (*distance risen*) $=$ (*work got out*).
d (*weights*) $\times$ (*distance fallen*) $=$ (*work put in*)

From these results we readily obtain the efficiency.

Incidentally, we obtain a practical measure of the force tio by dividing load by effort; and of velocity ratio by riding distance risen into distance fallen.

What would be the efficiency of our system of pulleys if e pulleys were weightless and moved without friction?

In this case we can easily calculate that to support a load 40 lb. the force at F would have to be 5 lb. Now raise L t. The rope at F must be pulled 8 ft. So we have:

Work got out of machine $= 40 \times 1 = 40$ ft.lb.
Work put into machine $= 5 \times 8 = 40$ ft.lb.

In this case the efficiency would be 100%. In practice, course, because of friction, etc., such an efficiency can ver be quite reached. This is true not only for a system pulleys but for *any* sort of machine.

While under ideal conditions (never realised in practice) e work got out of a machine would be equal to that put o it, it is certainly true that *the work got out of a machine n never exceed that put into it.* This very important statent is known as the ***Principle of Work.*** If it were not true, should be able to create energy, i.e. to violate the principle Conservation of Energy.

Efficiency, Force Ratio and Velocity Ratio. Suppose that by ystem of pulleys, or by any other machine, we are able by ans of an effort of w lb.wt., acting through x ft., to raise oad (or overcome a resistance) of l lb. through a distance y ft. By definitions already given,

$$\textit{force ratio} = \frac{l}{w}, \text{ and } \textit{velocity ratio} = \frac{x}{y}.$$

$$\therefore \quad \frac{\textit{force ratio}}{\textit{velocity ratio}} = \frac{l}{w} \div \frac{x}{y} = \frac{ly}{wx}$$

$$= \frac{\textit{work got out of machine}}{\textit{work put into machine}}$$

$$= \textit{efficiency}.$$

The relation between these three quantities—force ratio, locity ratio and efficiency—should be carefully remembered.

Example 1. *A certain system of pulleys has an efficiency of 7 and a velocity ratio of* 8. *What force would have to be exerte lift a weight of* 600 *lb.? If this weight is lifted* 3 *ft., calculate work* (i) *put into the system,* (ii) *got out of it.*

$$\frac{\textit{Force ratio}}{\textit{Velocity ratio}} = \textit{Efficiency}.$$

$$\therefore \quad \frac{\textit{Force ratio}}{8} = \frac{3}{4}.$$

$$\therefore \quad \textit{Force ratio} = \frac{3}{4} \times 8 = 6.$$

$$\therefore \quad \frac{\textit{load}}{\textit{effort}} = 6.$$

$$\text{But } \textit{load} = 600 \text{ lb.wt.}$$

$$\therefore \quad \textit{effort} = \mathbf{100\ lb.wt.}$$

If load is lifted 3 ft., effort acts through a distance of $3 \times 8 =$ ft. (because velocity ratio $= 8$).

$\therefore$ work put into machine $=$ *effort* $\times$ *distance*

$= 100$ lb.wt. $\times$ 24 ft. $=$ **2400 ft.l**

work got out of machine $=$ *load* $\times$ *distance*

$= 600$ lb.wt. $\times$ 3 ft. $=$ **1800 ft.lb**

The Inclined Plane. On p. 39 of *Junior Physics* we fo that if a body of weight W was being drawn up a smo inclined plane by a force P parallel to the plane (Fig. 6 then $\frac{P}{W} = \frac{h}{l}$, where h is the height of the plane and l its leng

It follows at once that $P = \frac{Wh}{l}$.

Let us see how this result squares with the principle of Work.

We may regard our plane as a 'machine' for enabling us to raise the object of weight W from the lower level BC to the higher level A.

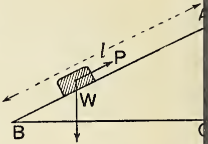


Fig. 6/4

i.e. Work got out of machine $= Wh$.

Work put into machine $=$ *force* $\times$ *distance*

$$= P \times l$$

$$= \frac{Wh}{l} \times l$$

$$= Wh$$

$=$ Work got out of machine.

Thus the principle is verified.

The Screw. The screw is a genuine machine in the sense in ich we are using the term. In the lifting jack, for instance, is used in raising the great weight of a motor-car.

You will learn a great deal about a screw by cutting out a ht-angled triangle ABC, and coiling it round a thin cylinder ch as a pencil. This will give you a ry fair model of a screw, as shown in g. 6/5. Suppose we are driving a screw o wood, or into a steel nut. When we e it one complete turn, it advances by amount indicated by KB in Fig. 6/5, i.e. the distance from one thread to the xt, measured along the axis of the cy- der. This distance is known as the *pitch* the screw.

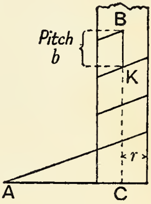


FIG. 6/5

It may conveniently be noted here that s relation between circumference and ch is made use of in the *micrometer screw gauge*. Sup- se, for instance, that the screw has a pitch of 1 mm. e have a horizontal scale (see Fig. 6/6) to show how many mplete turns of the screw have been made, and a circum- ential scale (CC′) to show e number of *hundredths* of urn. We can then readily ke a reading to the hun- edth of a millimetre. Thus e ball bearing in the figure s a diameter of 2·54 mm.

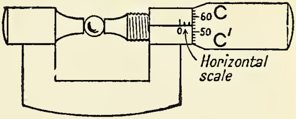


FIG. 6/6

We can find the force ratio d velocity ratio of the screw by considering it as a coiled lined plane. It is simpler, however, to make use of the inciple of Work, thus:—

Suppose the radius of the screw $= r$ and its pitch $= b$. t $E =$ force applied (horizontally, in the direction of a ngent to the cylinder), and $R =$ resistance overcome.

In one complete revolution the force E acts through a stance equal to the circumference, i.e. $2\pi r$. Hence,

$$\text{work put into machine} = E \times 2\pi r \quad . \quad . \quad \text{(i)}$$

the same time the screw overcomes a resistance R through listance b.

$\therefore$ work got out of machine $= \mathrm{R} \times b$ . . . (ii

But *in a perfect machine,* work put in = work got out.

$$\therefore \quad 2\pi r\mathrm{E} = \mathrm{R}b.$$

$$\therefore \quad \frac{\mathrm{R}}{\mathrm{E}} = \frac{2\pi r}{b}.$$

R/E is of course the force ratio, and it is evident that t smaller we make b, the greater is the force ratio. We c also increase the force ratio by increasing r. For practi purposes we do this by using a screw-driver with a bro handle; or by using a T-piece, as in the lifting jack, or the implement used for turning on a street hydrant.

$$\text{Velocity ratio} = \frac{\textit{distance through which effort acts}}{\textit{distance through which resistance is overco}}$$

$$= \frac{2\pi r}{b}$$

$$= \textit{force ratio.}$$

So far we have assumed a perfect machine, includi absence of friction; and velocity ratio = force ratio, as should expect. In the screw, however, the frictional sistance is very great. Thus the force ratio is much less th the velocity ratio, which is much the same thing as sayi that the efficiency is low.

Example 4. *A screw-jack is operated by a* T*-piece having cross-bar* 20 *in. long. The pitch of the screw is* $\frac{1}{4}$ *in. What fo would be required to lift a car weighing* 2000 *lb. if the efficiency the screw is* 25%?

Let required force be x lb.wt.

In one complete turn of T-piece, this force acts through distance of $20 \times \frac{22}{7}$ in. $= \frac{20 \times 22}{12 \times 7}$ ft.

$\therefore$ work put into machine $\frac{20 \times 22}{12 \times 7}\,x$ ft.lb.

Now, with one complete turn of T-piece, car rises $\frac{1}{4}$ in. $= \frac{1}{48}$ f

Efficiency is 25%, i.e. work got out $= \frac{25}{100}$ of work put in.

$$\therefore \quad \frac{2000}{48} = \frac{25}{100} \times \frac{20 \times 22}{12 \times 7}\,x$$

Solving this, we get $x =$ **31·9 lb.wt.**

The Lever. In Chapter 4 of *Junior Physics* we arrived by periment at the ***Law of the Lever.*** Where the forces are ting at right angles to the lever we may state it in the simple rm:—

Load $\times$ *Load Arm* $=$ *Effort* $\times$ *Effort Arm.*

In Fig. 6/7, for instance, we have $w \times \mathrm{FA} = \frac{1}{3}w \times \mathrm{FB}$. To include the kind of case represented in Fig. 6/8, we

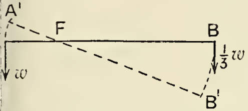


Fig. 6/7

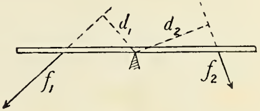


Fig. 6/8

ed the more general statement: *When a lever is at rest der the action of two forces, the product (force)* $\times$ *(perpendicular stance from the fulcrum to its line of action) is the same for th sides.* Mathematically, the law may be expressed by the uation $f_1d_1 = f_2d_2$.

Let us consider a simple lever in action—Fig. 6/7, for stance, can represent a crowbar AB with its fulcrum at F. 1 effort applied at B overcomes a resistance at A, and the rer moves into the position A′B′. The work put into the achine is the force at B multiplied by the distance BB′. e work got out of it is the *larger* resistance at A multiplied the *smaller* distance AA′. It is quite an easy exercise in nilar triangles to prove that the two amounts of work are ual—i.e. the Principle of Work holds good, as we should pect.

The Balance. A common and important example of the rer is the ordinary beam balance. Here the forces are eights, and we may write $w_1d_1 = w_2d_2$. In an accurately ade balance $d_1 = d_2$. Hence the d's cancel and $w_1 = w_2$; at is, the weight of the object is found by adding up the eights in the opposite pan.

If the d's are not equal, the weight of the object cannot be und in this simple way. In practice we may use what is

called the *method of substitution.* To do this, we put object in one pan and balance it by means of lead shot, sa etc. We then substitute weights for the object, mak them balance the lead shot. These weights evidently repres the weight of the object.

Another method is to weigh the object first in one pan and then in the other.

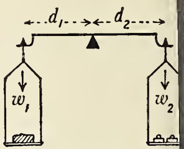


Fig. 6/9

Suppose the left arm of the balance measures d_1 cm., the right arm d_2 cm., and the true weight of the body is W gm. When the body is placed in the right-hand pan it is balanced by w_1 gm. in the left (Fig. 6/10*a*).

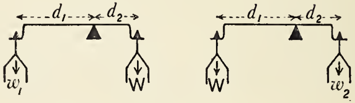
$$\therefore \quad w_1 d_1 = W d_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (i$$

Again, when placed in the left-hand pan it is balanced w_2 gm. in the right (Fig. 6/10*b*).

$$\therefore \quad W d_1 = w_2 d_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (ii$$

From (i), $\dfrac{d_1}{d_2} = \dfrac{W}{w_1}$, and from (ii) $= \dfrac{d_1}{d_2} = \dfrac{w_2}{W}$.

$$\therefore \quad \frac{W}{w_1} = \frac{w_2}{W}, \text{ giving } W^2 = w_1 w_2, \text{ or } W = \sqrt{w_1 w_2.}$$



(*a*) (*b*)

Fig. 6/10

Thus the true weight of the body is the *geometric mean* the apparent weights on the two different sides. In pract the arithmetic mean, $\frac{1}{2}(w_1 + w_2)$, is taken, as there is appreciable difference between this and the geometric me provided w_1 and w_2 do not greatly differ.

Problems on balances with unequal arms are easily solv by applying the law of the lever, as in the following.

Example 5. *The right arm of a balance is* 15·00 *cm. long, the* *t arm* 15·06 *cm., and the beam balances when no scale-pans are* *ached. If it also balances when the scale-pans are attached, and* *one on the left weighs* 50 *gm., calculate the weight of the other pan.* *Suppose an object is placed in the left-hand pan and the beam is* *rizontal when a* 100 *gm. weight is placed in the other pan, what is* *weight of the object?*

If R is the weight of the right-hand pan, we have (by the law the Lever),

$$R \times 15 = 50 \times 15{\cdot}06,$$

which gives $\mathbf{R} = \mathbf{50{\cdot}2}$ **gm.**

f x is the weight of the object, the total weight on the left i0 + x, and the total weight on the right is $100 + 50{\cdot}2 = 150{\cdot}2$.

∴ by the law of the Lever,

$$(50 + x) \times 15{\cdot}06 = 150{\cdot}2 \times 15{\cdot}00.$$

Solving this equation, we obtain $x =$ **99·60 gm.**

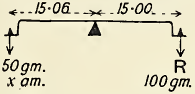


Fig. 6/11

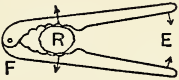


Fig. 6/12

Other 'orders' of levers. In all the levers mentioned in *nior Physics*, and in the balance just discussed, the fulcrum ies between E and R, where E is the point of application the effort and R of the resistance. Such levers are often d to be of the first 'order' or class.

n many cases, however (e.g. a pair of nut-crackers), R lies ween E and F. Such a lever is said to be of the *second er*.

Example 6. *In Fig.* 6/12 *suppose* RF = 2 *in. and* EF = 5 *in.* *we apply a force of* 6 *lb. weight at* E, *what pressure is experienced the nut at* R?

f the required pressure is x lb. weight we have by the law of Lever,

$$x \times FR = 6 \times EF$$

$$\therefore \quad x \times 2 = 6 \times 5$$

$$\therefore \quad x = \mathbf{15\ lb.wt.}$$

One is apt to become rather confused in applying the law the Lever in a case of this sort, and it is perhaps better to thi in terms of the Principle of Moments, though it really amounts the same thing. Thus taking moments about F we have

clockwise moment $= 6 \times$ EF

anticlockwise moment $= x \times$ FR.

$\therefore \quad x \times$ FR $= 6 \times$ EF, and we finish as before.

Levers of the *third order*, i.e. in which E lies between F and are met with in sugar-tongs and a common pattern of fi tongs. The pedal of a knife-grinder's maehine, or of a sewir machine, is also a lever of this kind, and so is the safety-val of a steam-engine (Fig. 6/14).

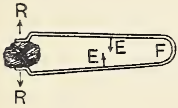


Fig. 6/13

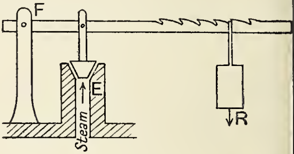


Fig. 6/14

Another interesting example is the human fore-arm. the elbow, may be regarded as the fulcrum, the load res in the hand at R, and the effort is applied at E, where t lower end of the biceps muscle is attached.

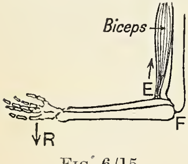


Fig. 6/15

Notice that in levers of the thi order, the force ratio is always less tha 1, because the effort arm is alwa shorter than the load arm. Suppos for instance, that at E (Fig. 6/15), w have to apply an effort e to overcome resistance r (practically a 'load') at Taking moments about F we have

clockwise moment $= e \times$ EF.

anticlockwise moment $= r \times$ FR.

$$\therefore \qquad \frac{\textit{load}}{\textit{effort}} = \frac{r}{e} = \frac{\text{EF}}{\text{RF}}.$$

But EF is less than RF.

$\therefore \quad \frac{r}{e}$, the force ratio, is less than 1.

orrespondingly of course the velocity ratio is less than 1. us the up-and-down distance moved by the knife-grinder's t for instance is less than that moved by the end of the lal—an arrangement which obviously makes for comfort. nilarly, a large up-and-down movement of one's fore-arm secured by a much smaller contraction and elongation of biceps.

Questions

A

. Fill in the blanks in the following table:—

Machine	Effort (lb. wt.)	Distance moved by effort (ft.)	Load (lb. wt.)	Distance moved by load (ft.)	Velocity ratio	Force ratio	Efficiency (%)
ver . .	...	2	99	1	...	...	99
ock and ickle (fig. 6/2)	12	16	...	4	...	...	75
clined plane ig. 6/4) .	20	5	...	...	$6\frac{1}{4}$	5	...

. Using the block and tackle of Fig. 6/2 on p. 52 a man is with an effort of $12\frac{1}{2}$ lb. wt. and by pulling in 8 ft. of rope aise a load weighing 45 lb. to a height of 2 ft. Find (i) the k put into the machine, (ii) the work got out of it, (iii) its iency.

. Find the force ratio and the velocity ratio of the machine . 2, and *hence* find the efficiency. Compare your answer with previously obtained.

B

. Describe how you would determine experimentally the iency (for one load) of a pulley system consisting of one fixed one movable block. The number of pulleys in each block be assumed unknown.

sack weighing 1 cwt. is lifted 30 ft. by such a system in which mechanical advantage is four and the efficiency 80%. ind the effort applied and the work done by it in lifting the . Neglect the weight of the lower block. *Lond.*

2. Define the *efficiency, mechanical advantage* and *veloc ratio* of a machine.

Give a labelled diagram of a machine suitable for lifting a lo of about 100 lb. wt. when a force of about 25 lb. wt. is availa to work it, and explain how it would be used. State the proximate value of the velocity-ratio of the machine and descr briefly how you would measure it. *Lond.*

3. A capstan is 1 ft. in diameter and has four bars at ri angles to the axle. One man pushes against each bar and ex a force of 50 lb. wt., so as just to raise an anchor weighing 1000 How far along the bars from the centre of the capstan's a must each man push? *O.C.**

4. Explain what is meant by the *mechanical advantage, veloc ratio* and *efficiency* of a machine, illustrating your answer reference to the raising of a body by moving it up an incli plane.

What horizontal force is required to move a barrel of m 500 lb. up a smooth inclined plane 10 ft. long inclined at 30° the horizontal, and what is the work done? *Lond.*

5. The following results were obtained in an experiment w a sheaved pulley system with two pulleys in each block:—

Load (lb.wt.) .	20	40	60	80	100
Effort (lb.wt.) .	14·3	16·7	22·1	28·6	35·7

Work out the mechanical advantage and efficiency for ea value of the load.

Plot a graph of efficiency (Y-axis) against load (X-axis) a comment on the shape of the graph. *Oxf.**

6. Explain the terms *mechanical advantage, velocity ratio* a *efficiency* when applied to machines.

Why is 'perpetual motion' considered to be impossible?

In raising a load 1 in. by means of a machine, the point application of the effort was moved a distance of 90 in. in direction of the effort. If the efficiency of the machine 30%, calculate the effort required to raise a load of 600 lb. *Ca*

7. A screw of pitch 1 in. is worked by a lever 7 ft. in leng If a force of 3 lb. wt. applied at the end of the lever is just suffici to raise a weight of 1000 lb., calculate (*a*) the velocity ratio, the efficiency of the machine, (*c*) the work done by the effort raising the weight 3 in. (Take π as $\frac{22}{7}$) *O.C.**

CHAPTER 7

COMPOSITION AND RESOLUTION OF FORCES

Junior Physics (Chapter 2) we discussed at some length e meaning of 'Force,' and finally arrived at the definition—**rce** is *that which changes, or tends to change, the state of rest motion of a body.* In Chapter 6 when dealing with parallel ces we met with the term *resultant*—the ***resultant of a mber of forces*** being *that single force which can take the ice of all the separate forces.*

In the present chapter we shall be concerned chiefly with e resultant of non-parallel forces, and we may very well gin by considering the following experiment.

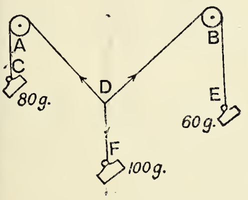


FIG. 7/1

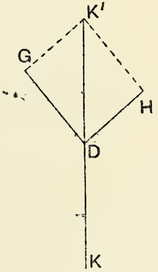


FIG. 7/2

Two light, smoothly-running pulleys A and B are fixed a board on the wall, and a piece of thread CADBE is passed er them. Weights are attached at the ends C and E, and hird weight F hangs from an intermediate point D by a rt branch thread. It does not greatly matter what weights actually used so long as no one of them is greater than the ier two put together, but for the sake of definiteness let suppose that the weights at C, E and F are 80 gm., 60 gm. 1 100 gm. respectively.

At the point D we have three forces acting—viz. (i) 80 gm. ng DA, (ii) 60 gm. along DB and (iii) 100 gm. along DF.

If we place a sheet of paper behind the threads we can ma the point that comes just behind D, and we can also ma the directions DA, DB, DF. These directions are shown Fig. 7/2.

On a scale of, say, 1 in. to 20 gm., represent the force 80 gm., acting along DA. This gives us DG (4 in.). Simila make DH 3 in. long and DK 5 in. long, to represent for of 60 gm. and 100 gm. respectively.

Produce KD to K′ making DK′ = DK.

Now, as DK′ is equal and opposite to DK, it represents upward force that would just balance the downward force 100 gm. (i.e. it represents the *equilibrant* of the downwa force—see *Jun. Phys.*, p. 55). But DG and DH, tak together, *also* represent the equilibrant of the downwa force (because in our experiment, the forces acting along D and DB were, together, able to balance the force along D In short,

(i) the equilibrant of the downward force is represent by DK′;

(ii) the equilibrant of the downward force is also represent by DG and DH.

It follows that the single force represented by DK′ c take the place of the two forces represented by DG and D In other words, DK′ represents the *resultant* of the two for represented by DG and DH.

If now we join K′G and K′H, we notice that the fig K′GDH is a parallelogram. Our first thought is that t is just a sort of accident, but on repeating the experimen number of times, constantly varying the weights, we find t the figure K′GDH is *always* a parallelogram. This gives a ready means of finding the resultant of two forces act at a point such as D. Draw two lines from D to repres the forces in magnitude and direction. Complete parallelogram. The diagonal drawn from D will give required resultant.

Another experiment leading up to the parallelogram rul this. Three pieces of string DA, DB and DF each ab a foot long are knotted together at D (Fig. 7/3) and a spr balance is attached to each. A large sheet of paper is pla

lerneath, and a well-marked dot is placed under D. The ing balances are now pulled by three boys, one to each ance, the pulls being regulated so that D remains over the . When a 'steady' condition has been reached, each boy es the reading of his balance, while a fourth boy quickly rks the paper to indicate the directions of the strings.

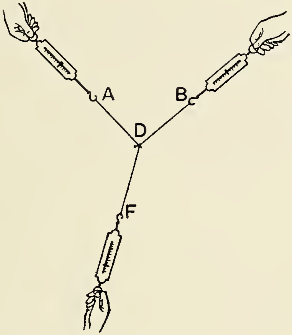


Fig. 7/3

Ve now have three forces in equilibrium, the magnitude direction of each being known, and the results are eloped in the way already described.

he conclusion which can be reached by experiments such hose we have described is known as the **Parallelogram Forces.** *If two forces acting at a point represented in magnitude and direction by adjacent sides of a parallelogram, their re- ant will be completely represented by that onal of the parallelogram which passes ugh the same point.*

his statement should be carefully com- ted to memory.

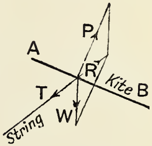


Fig. 7/4

good example of the parallelogram of es is seen in the flying of a kite. In Fig. 7/4 AB repre- s the kite seen sideways on. P represents the effective of the wind's pressure, and W the weight of the kite. By

the parallelogram of forces we can find R, the resultant o
and W. For equilibrium, T, the tension in the string, m
be equal and opposite to R.

Let us now work through one or two numerical examp
in which the Parallelogram of Forces occupies the cen
place.

Example 1. *There is a ship aground, and a tug is pulling i
towards the east with a force equal to 25 tons weight, while ano
is pulling north-east with a force equal to 15 tons weight.*

*Suppose a third tug is to take the place of these two, how hard m
it pull, and in what direction, so as to produce the same effect?*

Choosing a suitable scale (say 1 cm. = 5 tons) draw two li
AB and AC to represent forces of 25 tons to the east and 15 t
to the north-east respectively.

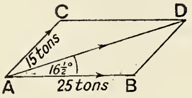


Fig. 7/5

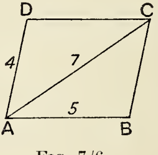


Fig. 7/6

Draw CD parallel to AB and BD parallel to AC. The result
is represented by AD. By careful measurement we find i
to be 7·42 cm. representing $7{\cdot}42 \times 5 = 37{\cdot}1$ tons, while
$\angle$BAD is found to be $16\frac{1}{2}°$.

Thus the answer is **37·1 tons weight in a direction $16\frac{1}{2}°$ N of**

Example 2. *Two forces of 5 lb. and 4 lb. weight respectively
at a certain angle. Find this angle, given that the resultant i
force of 7 lb. wt.*

If we imagine the complete parallelogram of forces to be dra
it would appear somewhat as shown in Fig. 7/6. Clearly
would be 4 units long (because opposite sides of a parallelogr
are equal). This suggests the necessary construction—

Make a triangle ABC, with AB = 5 units of length, BC =
units, and AC = 7 units. Complete the parallelogram ABC
Then BAD is the required angle, and is found by measurem
to be **76**°.

Triangle of Forces. Let us go back to Fig. 7/2 (for c
venience, repeated as Fig. 7/7) in which DG, DH and I
represent three forces in equilibrium. Now, these th

es are represented in magnitude and direction (but not regards their point of application) by the three sides of triangle DHK′. For comparing the sides of this triangle n DH, DG and DK, we see that—

is unchanged.

′ = DG and is in the same direction, though it is not rawn from the point D.

) = DK and is in the same direction, but drawn *towards* the point D instead of way from it.

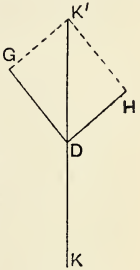


FIG. 7/7

he situation is summed up by a statement wn as the **Triangle of Forces,** viz. *If three es acting at a point are in equilibrium, they be represented in magnitude and direction ugh not in position) by the three sides of a ngle taken in order.*

Three sides of a triangle taken in order' ns that the end-point of one side is reled as the starting point of the next. s after DH (ending at H), the next side is HK′, *not* K′H.

xample 3. *A mass of* 6 *lb. hangs from the end of a light string, long. What force, applied by another string attached to the e point of the mass and inclined at* 45° *to the horizontal, will be ired to pull the mass aside to a distance of* 2 *ft. from the vertical ugh the point of suspension? (The problem may be solved r graphically or by calculation.)* J.M.B.*

he mass of 6 lb. is in equilibrium under the action of three es. (i) Its own weight acting along BC, vertically downds; (ii) the tension of the 4 ft. string, acting along BA; (iii) tension of the other string acting along BD (Fig. 7/8a).

nce these forces are in equilibrium, they can be represented he three sides of a triangle (except as regards their point of ication). Accordingly (Fig. 7/8b), draw PQ vertically nwards, and 6 units long (to represent 6 lb.). From Q, v QR parallel to BD, and from P [1] draw PR parallel to AB. 'e are asked to find the force along BD. This is represented

Strictly, after PQ and QR we should draw RP (not PR), so that sides would be 'taken in order.' As P is already fixed in position, more convenient to draw PR, but of course the force along BA presented by RP (not PR).

by QR, which is found to measure 3·11 units. The requi force is therefore **3·11 lb.wt.**

If required, we could easily (by measuring RP) find the tens in the string BA.

N.B. It is a little easier to let BC itself (extended t length of 6 units) serve, instead of PQ, as one side of triangle (Fig. 7/8*c*). We then draw CH parallel to BD, the third side HB is in line with BA. The required force of course, represented by CH.

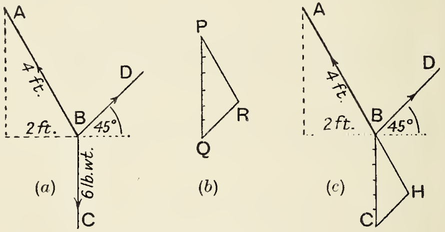


FIG. 7/8

Equilibrium of large body. So far, in this chapter, we h considered the case in which a small body—a point—is equilibrium under the action of three co-planar forces (forces in the same plane). We must now consider the c in which the body concerned is of appreciable size. We sh show that in this case the lines of action of the three forces either (i) all parallel or (ii) all pass through the same point

In our earlier book we have already had instances in wh a body of some size is in equilibrium under the action *parallel* forces (e.g. the wooden ruler on p. 35). In that ca we frequently made use of the fact that the sum of the clo wise moments about any point in the plane must be eq to the sum of the anticlockwise moments, or—more shortly that the algebraic sum of the moments about any point in plane must be zero. If this were not so, the body could be in equilibrium—it would rotate.

Suppose, however, the lines of action of the three for (say A, B and C in Fig. 7/9) are not all parallel. Then

st two of them, say A and B, must meet if produced. Let ·m meet at O. The two forces A and B may be replaced a single resultant, R. Find this resultant by the parallelo-m of forces or otherwise.

The body is now in equilibrium under the action of *two* ces, C and R, which must therefore be equal and opposite,[1] they must have a resultant of zero.

But the line of action of R passes through the point at ich A and B intersect.

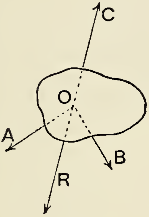


Fig. 7/9

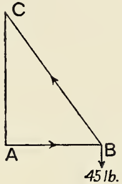


Fig. 7/10

Therefore C (which is in the same straight line as R) also ses through the point at which A and B intersect—i.e. A, nd C all pass through the same point.

Summing up, if a body is in equilibrium under the action of ee non-parallel co-planar forces, the lines of action of these ces must meet in a point, and the resultant of the forces st be zero.

Let us now consider some further examples related to the angle of Forces.

Example **4.** *Explain the rule known as the* parallelogram of es, *and show how it can be tested experimentally.*

l horizontal pole 3 *ft. long, with one end hinged to a vertical wall, ports, by a wire from its other end, a large electric sign weighing lb. Fastened to the end of the pole remote from the wall is a*

[1] If this is not clear, think of a board with two pegs to which strings attached. The strings are pulled. Obviously the board will move id until the strings are in the same straight line.

gain, unless the forces along the strings are equal, the board will e in the direction of the greater force.

hus the board will not be in equilibrium unless the two forces are al and opposite.

supporting wire 5 ft. long, fixed to the wall vertically above the p Find graphically the forces acting in the pole and wire. J.M.B.

For first part of question see pp. 65–67.

The arrangement of the pole, etc., is shown in Fig. 7/10, wh AB represents the pole and BC the wire.

At B we have three forces in equilibrium

(i) wt. of electric sign, 45 lb. downwards,
(ii) tension of wire acting along BC,
(iii) thrust of pole acting along AB.

Since the forces are in equilibrium, we can represent them the three sides of a triangle taken in order.

It is usually necessary to draw such a triangle, but in Fig. 7 it already exists, viz. the triangle ABC. (CA representing weight of 45 lb., AB the thrust and BC the tension.)

Now, AB = 3 units of length, BC = 5 units and by measu ment or calculation CA = 4 units.

	4 units of length represent	45 lb.
∴	1 ,, ,, ,, ,,	$11\frac{1}{4}$ lb.
∴	AB (3 units) ,, ,,	$11\frac{1}{4} \times 3 = 33\frac{3}{4}$ lb.
and	BC (5 ,,) ,, ,,	$11\frac{1}{4} \times 5 = 56\frac{1}{4}$ lb.

Thus **a thrust of $33\frac{3}{4}$ lb.wt. acts along AB and a tension $56\frac{1}{4}$ lb.wt. along BC.**

Resolution of Force. We have seen how a number of for can be compounded to give a single resultant. Convers a given force may be 'resolved' into a number of compone (in practice usually two), acting in specified directions.

Suppose, for instance, we have a force of 5 lb.wt. acting to the south, and we wish to resolve it into two components, one acting 20° E. of S. and the other 30° W. of S.

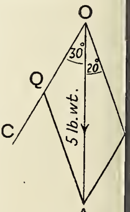


Fig. 7/11

Draw OA 5 units long to represent the 5-lb. force acting to the south, and draw OB and OC in the specified directions.

From A draw AP parallel to CO cutting OB in P, and AQ parallel to BO meeting OC in Q. By parallelogram of forces, OA represents the resultant of forces represented by OP and OQ. Conversely, OP and OQ represent the *resol parts,* in the directions OB and OC, of the force represen

OA. By measurement, OP is found to represent a force of ‡ lb.wt., and OQ one of 2·2 lb.wt.

We can illustrate the process experimentally by a very ght modification of the 'spring-balance' experiment de-ibed on p. 67.

Draw OA, OB and OC in the specified directions, and oduce AO to A′ (Fig. 7/12). Three boys now take spring ances attached to knotted strings as already described. The knot is placed over O and the balances are extended along OA′, OB and OC respectively. The reading along OA′ is adjusted to 5 lb., and the boys pulling in the other

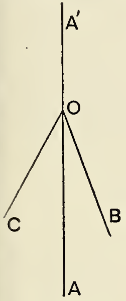


Fig. 7/12

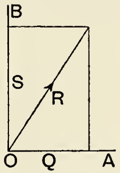


Fig. 7/13

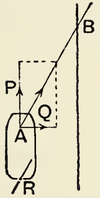


Fig. 7/14

ections increase or reduce their tensions accordingly. It uld be found, of course, that the reading along OB is lb., while that along OC is 2·2 lb.

omponents at right angles. It is often necessary to resolve given force into two components at right angles to one other; we shall have examples presently.

Notice that when we speak of the resolved part of a force ng a given line, it is understood that the other component it right angles to that line. Thus in Fig. 7/13 Q is the olved part of R along OA.

llustrations. There are numerous cases in daily life in ch we have to consider the resolution of a force into two nponents at right angles. For instance, you have seen arge towed along a canal from the tow-path, and it perhaps ns curious that it preserves a movement parallel to the k instead of following the direction of the tow-rope.

But suppose AB is the tow-rope. The tension along A
may be resolved into

(i) a force P parallel to the bank, which pulls the bo
forward,

(ii) a force Q at right angles to the bank. This gives
a tendency to turn inwards, which is counteract
by a suitable setting of the rudder (Fig. 7/14).

Somewhat similar is the case of a boat sailing into t
wind. Suppose AB is the boat's sail and the wind is blowi
from the direction CD. Resolve the wind's force into
acting at right angles to the surface of AB, and Q acti
along it. As there is not much friction the effect of Q m
be neglected. Now resolve P into two components, S
right angles to the length of the boat and T in a forwa

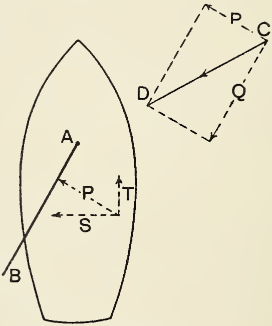


Fig. 7/15

direction. It is T that drives the boat along. S causes
to 'make leeway,' but this is reduced by the use of a keel
'centre-board.'

The aeroplane. Suppose an aeroplane is taking off, a
owing to the action of the propellor is moving rapidly fr
left to right along the ground. Relative to the plane, t
air of course moves from right to left. Chiefly owing to t
shape of the wing, there is a region of high pressure form
below it and of low pressure above it, and the net effect is
produce an upward force (represented by F in Fig. 7/

ırly at right angles to the wing. We can resolve F into ertical force L and a horizontal one D. L is known as *lift*, and if the plane is to rise it must obviously be a little ater than the total weight. D is the *drag*, and resists the vard movement of the aeroplane. It has to be overcome the pull of the propellor.

'he magnitude of L evidently depends that of F, which in turn depends on v fast the aeroplane is being moved. his movement is too slow L will not great enough to lift the aeroplane. Ve have the same principles at work n a boy is beginning to fly his kite. this case, he runs along the ground ead of setting the propellor to work.

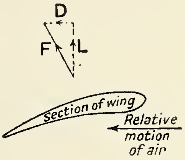


Fig. 7/16

Questions

A

By a graphical method or otherwise, find the resultant of following forces:

(i)	3 lb.wt. and	4 lb.wt. acting at an angle of		90°.
ii)	20 gm. ,,	30 gm. ,,	,,	180°.
ii)	20 gm. ,,	30 gm. ,,	,,	0°.
v)	3 lb. ,,	3 lb. ,,	,,	60°.
v)	10 lb. ,,	10 lb. ,,	,,	45°.

Two forces, one of them of 6 lb.wt., act at right angles and e a resultant of 10 lb.wt. By a graphical construction, or erwise, find the magnitude and direction of the other force.

A common method of hanging a picture is by means of a l passing like an inverted V over a nail. Chiefly by means diagram, point out the forces that are in equilibrium at the ıt of suspension.

B

State the theorem of the parallelogram of forces and describe explain an experiment to verify it.

he resultant of two forces is of magnitude 150 lb.wt. and ces angles of 25° and 60° with them. Find, by a graphical hod, the magnitudes of the forces.

An unknown mass is suspended by a light cord and is acted n by a horizontal force of 100 gm.wt. In the position of

equilibrium the cord makes an angle of 30° with the vertic[al]. Draw a force diagram and find the value of the mass. *Lond.*

3. Under what conditions will (*a*) two forces, (*b*) three for[ces] acting at a point, be in equilibrium?

Three spring balances are attached to a small ring. Two [are] pulled horizontally, one due north and the other south-east, t[heir] respective readings being 8 lb.wt. and 12 lb.wt. In wh[at] direction must the third spring balance be pulled in order th[at] the ring may be kept at rest? What will be the reading on t[his] balance? *Lond.*

4. The bob of a simple pendulum, hanging vertically, has [a] mass of 30 gm. A silk thread is attached to the bob and pulled horizontally. If the silk breaks when the tension in [it] exceeds 10 gm.wt., find (*a*) the maximum inclination of t[he] pendulum with the vertical, (*b*) the tension in the string of t[he] pendulum in that position. *Lond.**

5. Why is it better to tow a barge along a canal, from t[he] tow-path, by using a long rope rather than a short one? *Lon[d.]*

6. To the ends of a straight uniform beam of length 4 ft. a[nd] mass 5 lb. are secured the ends of a cord 8 ft. long. The beam [is] then hung in a horizontal position by passing the cord over [a] fixed hook. What is the tension in the cord? *Dur.**

7. Explain what is meant by the *triangle of forces*. Give [a] *brief* description of an experiment, carried out by you, to ver[ify] the principle.

A uniform bar of metal AB, weighing 80 lb., is suspended [by] two strings, AC and BC, fastened to a nail at *C*. If the strin[gs] make angles of 45° and 30° respectively with the horizon[tal], determine graphically, or otherwise, the tension in each stri[ng]. *C.W.B.*

8. A mass of 50 lb. is supported by two threads inclin[ed] respectively at angles of 60° and 30° to the vertical. Calcul[ate] the tensions in the threads. *O.C.**

9. Forces of 50, 40 and 30 gm.wt. act at a point in directi[ons] north, east and south respectively. Find their resultant [in] magnitude and direction. *Lond.**

10. A uniform rod, AB, 5 ft. long and weighing 10 lb., is s[us]pended by strings OA and OB. OA = 4 ft., OB = 3 ft. [On] squared paper, using a scale of 1 in. = 2 lb., draw a diagram [of] the forces acting on the rod when it is at rest, and mark cle[arly] what each line represents. By direct measurements, find [the] tension in each string. *Camb.**

11. A kilogram weight is placed on a smooth plane incli[ned] to the horizontal at 60° and is kept from sliding down by a str[ing] parallel to the plane. Calculate the tension in the string a[nd] the reaction between the weight and the plane. *Camb.**

CHAPTER 8

MOMENT OF A FORCE. CENTRE OF GRAVITY

ıs chapter will consist largely of a revision of the material died in Chapters 5 and 6 of *Junior Physics*, but we shall ısider some examples that would have been too difficult inclusion in the earlier book.

First, then, let us recall the meaning of 'moment of a ce.' ***The moment of a force about a fixed point*** is *the duct of the force itself, and the perpendicular distance from fixed point to the line of action of the force.*

Thus in Fig. 8/1, P is the fixed point, and the force F is

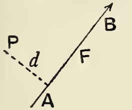


FIG. 8/1

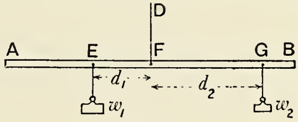


FIG. 8/2

resented by the straight line AB. If the perpendicular ance from P to AB is d, then the moment of F about the nt P is given by the product $F \times d$.

The moment of a force about a point as just defined is a ısure of the *turning powers* of the force about that point. s is best seen by considering a lever, balanced by forces resented by weights. In the case indicated in Fig. 8/2 s shown by experiment that $w_1 \times d_1 = w_2 \times d_2$—i.e. *moments* of the forces represented by w_1 and w_2 are equal.

But the *turning powers* of these two forces are also equal, w_2 tends to turn the lever clockwise and w_1 tends to turn nticlockwise; and as the lever remains horizontal, these dencies must be equal and opposite. Hence the moment force must be a measure of its turning power.

Principle of Moments. By hanging extra weights on the of Fig. 8/3 we could evidently arrange for it to be in ilibrium under the action of more than two forces. ther, though all these 'weight' forces are downwards, we ld easily arrange to apply some upward forces by means of

spring balances—such a force is shown as w_5. If we no the weights (or balance readings) and distances, it would found that $(w_2 \times d_2) + (w_4 \times d_4) = (w_1 \times d_1) + (w_3 \times d_3)$ $(w_5 \times d_5)$.

i.e. sum of the clockwise moments = sum of anticlockw moments.

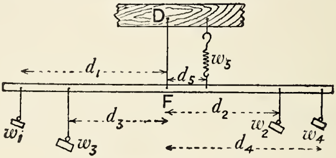


FIG. 8/3

This is an example of the **Principle of Moments** which sta that: *When a bar free to move about a fixed point is equilibrium, the sum of the clockwise moments is equal to sum of the anticlockwise moments.*

Some examples involving the principles just discus were given on pp. 30–36 of our earlier book. Here are or two harder ones.

Example 1. *Explain the term* moment of a force about a poi *Two uniform rods* AB, BC, *of different materials, each* 50 *long, are joined at* B *in a straight line. On hanging a* 50- *weight from* A, *it is found that the combination balances on a kn edge* 20 *cm. from* A. *When the* 50-*gm. weight is hung from* C, *point of balance is* 40 *cm. from* C. *Find the weight of* AB *and*
J.M.B

For first part of question see p. 77.

Suppose the required weights are w_1 and w_2 respectiv The rods are uniform, and so we may regard w_1 as acting at the middle point of AB, and w_2 at E, the middle point of Let F be the knife-edge.

$$AD = \tfrac{1}{2}\,AB = 25 \text{ cm.};\quad AF = 20 \text{ cm. (given).}$$

$$\therefore\quad FD = AD - AF = 5 \text{ cm.};\quad FE = FD + DE = 5 + 50 = 55 \text{ cm.}$$

Taking moments about F, we have

$$\begin{aligned}\textit{Sum of clockwise moments} &= (w_1 \times FD) + (w_2 \times FE)\\ &= 5\,w_1 + 55\,w_2\\ \textit{Anticlockwise moment} &= 50 \times AF\\ &= 50 \times 20 = 1000\end{aligned}$$

$$\therefore\quad 5\,w_1 + 55\,w_2 = 1000$$

$$\text{or } w_1 + 11\,w_2 = 200 \quad . \quad . \quad . \quad . \quad . \quad (i$$

urning now to Fig. 8/4*b*, it is easily shown that FE = 15 cm., = 35 cm., while FC = 40 cm. (given).

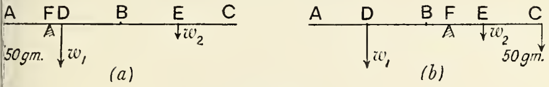


FIG. 8/4

$$\textit{um of clockwise moments} = (w_2 \times \text{FE}) + (50 \times \text{FC})$$
$$= 15\,w_2 + 2000$$
$$\textit{nti-clockwise moment} = w_1 \times \text{DF} = 35\,w_1$$
$$\therefore\quad 35\,w_1 = 15\,w_2 + 2000$$
$$\text{or } 7\,w_1 - 3\,w_2 = 400 \quad . \quad . \quad . \quad . \qquad \text{(ii)}$$

olving (i) and (ii) as simultaneous equations, we obtain = **62½ gm.** and w_2 = **12½ gm.**

xample 2. *A uniform rod of length* 8 *ft. weight* 8 *lb. is hinged smoothly at one end vertical wall; it is kept in a horizontal posi- by a string attached to the free end of the rod, to a point in the wall vertically above the e and* 6 *ft. from it. What is the tension in string?* J.M.B.*

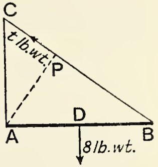


FIG. 8/5

et AB be the rod hinged at A, AC being vertical wall.

= 8 ft. AC = 6 ft. ∴ BC = $\sqrt{\text{AB}^2 + \text{AC}^2} = \sqrt{64 + 36}$ = 10 ft.

he rod is in equilibrium under the action of the clockwise nent 8 × AD, and the anticlockwise moment t × AP, re t (lb.wt.) is the required tension, and AP is the length of perpendicular from A to BC.

$$\text{i.e. } 8 \times \text{AD} = t \times \text{AP} \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(i)}$$

$$\text{Now by similar } \Delta^s,\ \frac{\text{AP}}{\text{AC}} = \frac{\text{AB}}{\text{BC}}$$

$$\therefore\quad \text{AP} \div 6 = 8 \div 10.$$
$$\therefore\quad \text{AP} = 4{\cdot}8 \text{ ft.}$$
$$\text{Also AD} = \tfrac{1}{2} \text{ of } 8 \text{ ft.} = 4 \text{ ft.}$$

Substituting these values in (i), we have $8 \times 4 = t \times 4{\cdot}8$

$$\therefore\quad t = \mathbf{6\tfrac{2}{3}\ lb.wt.}$$

he problem may also be solved as an exercise in the Triangle orces (cf. Ex. 3 on p. 71).

Example 3. *A uniform ladder 20 ft. long and weighing* 100 *stands against a smooth wall with which it makes an angle of* 3 *A horizontal force which increases as required up to* 60 *lb.wt.* *on the base, towards the wall. How far can a boy weighing* 80 *go up the ladder before it will slip?*

The arrangement is shown in Fig. 8/6.

As the wall is smooth, the reaction AR is at right angles to it. This reaction is equal and opposite to the force at B. The boy is supposed to be at P.

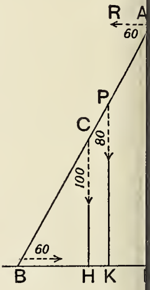


Fig. 8/6

Imagine an axis at B, perpendicular to the paper, and let us take moments about it.

The reaction at A has an anticlockwise moment ($= 60 \times$ AD). The weight of the ladder has a clockwise moment ($= 100 \times$ BH), and so has the weight of the boy ($= 80 \times$ BK). As he moves higher up the ladder, BK increases, and if the clockwise moment should become too great, A will descend and B move outwards, the ladder will slip.

For equilibrium, we must have

$$60 \times AD = (100 \times BH) + (80 \times BK) \quad . \quad . \quad \text{(i}$$

Now $AD = AB \sin 60° = 20 \times \sqrt{\tfrac{3}{2}} = 17{\cdot}32.$

$BH = \tfrac{1}{2}BD = \tfrac{1}{2}AB \cos 60° = \tfrac{1}{2} \times 20 \times \tfrac{1}{2} = 5.$

$BK = BP \cos 60° = x \times \tfrac{1}{2}$, where x is the required dista up the ladder.

Thus equation (i) becomes

$$60 \times 17{\cdot}32 = (100 \times 5) + (80 \times \tfrac{1}{2}x).$$

Solving this, we get $x =$ **13·5 ft.**

N.B. The force at B is supplied by friction. We shall later (p. 87) that, *up to a certain maximum*, this force is alw just enough to resist slipping. If it were = 60 lb.wt., when boy began to ascend the ladder, the latter would slip *up* the w In practice, a man stands at the base of the ladder so that can add to the horizontal force if necessary.

Let us now recall, and to some degree extend, the work Parallel Forces and Centre of Gravity which formed subject of Chapter 6 in *Junior Physics.*

We found that, in general,[1] a group of parallel forces ha single resultant, of which

[1] The exception is the case in which the parallel forces form a *co* (p. 82).

i) the *magnitude* is equal to the sum of the parallel forces,

i) the *direction* is that of the parallel forces and

i) the *point of application* is such that the sum of the clockwise moments about that point is equal to the sum of the anticlockwise moments.

simple example is shown in Fig. 8/7, where parallel s of 4 lb.wt. and 2 lb.wt. are acting at right angles to r AB 3 ft. long. The resultant R (i) has a magnitude + 2 = 6 lb.wt.; (ii) has a direction llel to that of the given forces and acts at a point C, 1 ft. from A, use at this point the moment of the force about C (4 × 1) is equal to of the 2 lb. force (2 × 2).

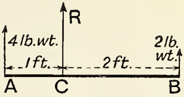


Fig. 8/7

r simplicity the forces in Fig. 8/7 shown acting at right angles to the bar, but the statements e with regard to the resultant are true whatever the angle be.

rallel forces acting in the same sense (e.g. all to the north, l to the east) are said to be *like*. If they act in opposite s (e.g. some to the north and some to the south) they are to be *unlike*. The statements made with regard to the ltant still hold good, except that forces acting in opposite tions must be regarded as being of opposite *sign*.

cample 4. *Unlike parallel forces of* 4 *lb.wt.* and 2 *lb.wt. act ght angles to a bar* AB 6 *feet long, their points of application the ends* A *and* B *respectively. What will be the direction, itude and point of application of their resultant?*

rection. Parallel to the lines of action of the given forces, n the same sense as the greater one.

agnitude. Calling the given forces + 4 lb.wt. and − 2 lb.wt. nagnitude = + 4 − 2 = + 2 lb.wt.

int of application. Suppose this is at C (Fig. 8/8), where = x ft. (C cannot lie between A and B, because in that case moments would be clockwise). Taking moments about C,

clockwise moments = anticlockwise moments

$$2 \times BC = 4 \times AC$$

$$\therefore \quad 2(3 + x) = 4x$$

$$\therefore \quad x = 3.$$

$$AC = \textbf{3 feet.}$$

Couples. A pair of *equal* unlike parallel forces is known a *couple.* In this case the forces simply tend to rotate body to which they are applied, and they cannot be repla by a single resultant.

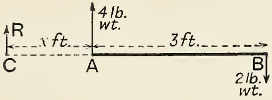


FIG. 8/8

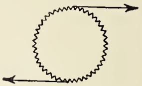


FIG. 8/9

We have a common example of a couple when windin watch or clock with a key, or a watch with a stem-win (Fig. 8/9). Another case occurs when we spin a top holding it between the thumb and fore-finger and giving i sharp turn. Notice that in all such cases it is impossible secure the same result by applying a *single* force.

Centre of Gravity. In *Junior Physics*, p. 57, we regarde body as being made up of a great number of separate partic

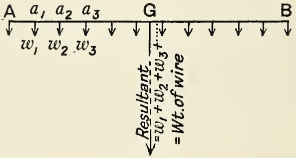


FIG. 8/10

each with its own weight (w_1, w_2, w_3 . . .). Thus the b is acted upon by a great number of small, like, parallel for The resultant of these is a single force whose magnitud $w_1 + w_2 + w_3 \ldots = W$, where W is the weight of the bo and whose direction is the same as that of the parallel for i.e. vertically downwards. It was explained further that whole weight of the body might be regarded as acting thro a particular *point* (G in Fig. 8/10) known as the *centre gravity.* If we move the body to another place, this poi of course, moves with it, but it does not move *relative to body.* We may now formally define the ***centre of gravity*** a body as *that point, fixed relative to the body, through wh its weight may always be supposed to act.*

Note the 'always.' In Fig. 8/11*a* the weight of the body :s through the point H as well as G. If the body be turned ınd (Fig. 8/11*b*), the weight still acts through G, but not ·ough H. G is the only point through which the weight *ays* acts.

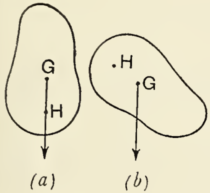


FIG. 8/11

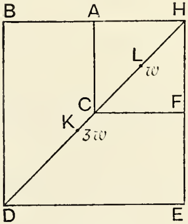


FIG. 8/12

n Chapter 6 of *Junior Physics* we considered certain perties of the centre of gravity, e.g. how its position may ide whether the equilibrium of a body shall be stable, table or neutral. We also discussed some practical thods for finding the position of the c.g. We shall now sider an example in which the position of the c.g. is nd by calculation.

:xample 5. A square of metal, whose sides are 4 in. in length, one quarter cut away so as to leave an L-shaped piece.
how by means of a full-sized diagram the position of the centre ravity of the piece of metal and explain your construction.
low would you check your result by experiment? Lond.

uppose BDEH was the original square from which the quarter HA has been cut away (Fig. 8/12).

f the portion removed weighs w, the remaining L-shaped e evidently weighs $3w$.

rom the symmetry of the figure, we can see that both K the of the L-shaped piece and L the c.g. of the square ACFH on the diagonal DCH.

magine that the square ACFH is replaced and that the com- e square BDEH, in a horizontal plane, is balanced on a ıted support placed under C. KCL now becomes our 'weight- lever' balancing at C, because the clockwise moment of the e w, acting at L, is equal to the anticlockwise moment of force $3w$, acting at K.

e. $$w \times \text{LC} = 3w \times \text{KC}$$

$$\therefore \quad \text{KC} = \tfrac{1}{3}\,\text{LC}.$$

G

Thus it only remains to measure LC on a full-sized diagra and make CK equal to one-third of it.

The result could easily be checked experimentally, e.g. showing that the sheet of metal balances on the end of a pen placed just below K (this and other methods are fully describ in *Junior Physics*, pp. 57–9).

Questions

A

1. A 20-in. scale is suspended from a point half-way along and a 50-gm. weight is hung at a distance of 3 in. from this poi Where would (i) a 20-gm. weight, (ii) a 100-gm. weight have be placed, to balance it?

2. The 50-gm. weight, placed as above, is balanced by me of a pocket-knife hung at a distance of 4 in. from the fulcru Find the weight of the pocket-knife.

3. The scale of q. 1 is suspended at the division marked (in.), but hangs horizontally when a 10-gm. weight is hung at Find the weight of the scale.

4. The scale of q. 1 is suspended from its middle point, a weights of 20 gm., 10 gm. and 100 gm. are hung at the poi marked 2 in., 4 in. and 8 in. respectively. Where must a 50- weight be hung in order that the scale may balance horizontal

5. On a sheet of cardboard draw a triangle of sides 4 in., 5 and 6 in., and by a geometrical method find its c.g. Now the triangle out, and by balancing it on a pencil find wheth you have obtained the point correctly.

B

1. A uniform ladder of mass 200 lb. rests on a pavement agai a smooth wall at an angle of 60° to the horizontal. A boy mass 100 lb. climbs up the ladder, which is prevented from slippi by a force of 100 lb. applied horizontally at the foot of the ladd By what fraction of the ladder's length can the boy ascend bef the ladder slips? *O.C.*

2. Four forces act along the edges of a wooden square AB of 6-in. side. The forces are 10 lb.wt. along AB, 15 lb.wt. al BC, 10 lb.wt. along CD and 15 lb.wt. along DA. Find t moment of the couple required to keep the body from rotati *Oxf.*

3. Explain the meanings of (*a*) the moment of a force ab an axis, (*b*) the centre of gravity of a body.

A metal box has for its upper side a square lid of unifo thickness hinged at one of its edges. The mass of the lid is 5 and the length of an edge is 4 ft. The lid is opened by applyi a vertical force at the edge opposite the hinge. Find (*a*)

rce required to incline the lid at 60° to the horizontal, (*b*) the rce at the hinge in this position, (*c*) the work done in raising e lid from the horizontal to the vertical position. *Dur.*

4. A telescope consists of four concentric tubes, each 10 in. in ngth, their masses being 4, 3, 2 and 1 lb. Find, by calculation, e position of the centre of gravity. *O.C.**

5. If masses of 1, 2, 3 and 4 lb. are placed at the corners of a uare of 10-in. side, taken in order, calculate the position of the ntre of gravity. *O.C.**

6. From a thin square plate ABCD of uniform density, and th centre E and sides of 8 in., the triangle AED is cut out. etermine the position of the centre of gravity of the figure nich is thus obtained. *O.C.**

7. What are the conditions which must be satisfied when three rces, acting on a small body, keep it in equilibrium?

A uniform rod AB, 10 ft. long and weighing 12 lb., is hinged a vertical wall at A, and is held at an angle of 30° to the ver- al by a horizontal string which is attached to the rod at a int 2 ft. from B and pulls the rod away from the wall. Find aphically (or by calculation), the magnitude and the direction the reaction at A and the magnitude of the tension in the ing. *Camb.*

8. Explain the meaning of the term *centre of gravity* of a body. A body with a flat base is tilted about one edge. Explain the ect of the position of the centre of gravity of the body on the aximum possible angle of tilt before unstable equilibrium is ached.

A compound cylindrical rod 12 in. long is made of two uniform linders, each 6 in. long and placed end to end. One is of wood specific gravity 0·4 and the other of cork of specific gravity 24, both being of the same area of cross-section. Calculate the sition of the centre of gravity of the rod and say briefly how u would check the position by experiment. *Lond.*

9. Describe how the centre of gravity of an irregularly shaped rdboard sheet can be found experimentally.

A rough aeroplane model is T-shaped, made of cardboard and in one plane. The wing span is 50 cm. and its breadth 4 cm.; e length of the fuselage is 40 cm. and its breadth 3 cm.; the ight of the cardboard is 0·20 gm. per sq. cm.; and the weight the engine, 18·00 gm., may be supposed concentrated at the ddle of the leading edge of the wing. The model rests in a rizontal plane when suspended by a single vertical wire. Find e point of attachment of the wire and the tension in it. *J.M.B.*

CHAPTER 9

FRICTION

FRICTION is the force called into play when one surfac moves over another. Thus we experience friction when w drag a desk across the school floor, or when we try to pull nail out of a piece of wood. In our previous work we hav often found it necessary to refer to this force, as in Chapter where we considered the part that it played in the act walking, in the case of a horse pulling a cart, etc. We mu now study the subject more closely.

If friction ceased. It is instructive to reflect for a littl while on what would happen if the force of friction suddenl ceased to exist. Suppose you were on a level road on yo way to school when the change occurred. You would n longer be able to walk. You might fall, or you might remai on your feet, but in either case you would continue to mo forward in the same straight line (Newton's 1st law) until y met with some obstacle—a wall, or some unfortunate movi in the opposite direction. If you happened to be goi downhill at the moment when friction ceased, you wou move with ever-increasing speed until you met with a obstacle. If going uphill, however, you would soon beg moving backwards—you would not be able to turn roun Perhaps the most happily-placed boy would be one who h happened to turn round and stop just before the sudd collapse of friction. By blowing gently he would be able move in the required direction.

Things would be little better if friction had ceased in t course of a lesson. The master in the act of writing on t blackboard would move backwards towards his class, b the boys would not be in a position to enjoy such a delicio situation because the desks on which they were sitting wou have collapsed—for nails and screws owe their grip to frictio Not many of the fallen would wish to pursue their studi amid the wreckage, but if they did, the fact that lead penc had slid out of their wooden sheaths and pen-nibs from th holders would add to their troubles. However, you c

ntinue the theme for yourself. Let us get back to the world
know.

Friction and heat. In the case of a machine, we have seen ain and again that work put in is (at least to a large extent) presented by work got out. But when we do work in ercoming friction there is, so to speak, nothing to show for it. tually it is converted into heat.

To raise the efficiency of a machine, we must evidently range that as little work as possible shall be spent in overming friction, and hence the need for *lubrication*. Instead allowing one metal surface to rub against another, we range that the two surfaces shall be separated by a thin n of oil or grease.

Limiting friction. Suppose a wooden block is resting on a ble, with a spring balance attached to it. We pull with a

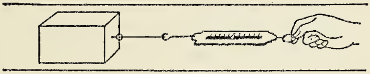


Fig. 9/1

ce, say, of 20 gm., and the block does not move. Why not? idently because a frictional force of 20 gm., in the opposite ection, has been called into play.

We increase the forward pull to 25, 30, 35 gm., and still block does not move. Friction is evidently a force which vary, within limits, so as to be exactly equal and opposite the forward pull on the body concerned.

But when this forward pull has been increased to a certain ount—say, 40 gm.—the wooden block begins to move. friction of which we have been speaking has a limiting ue, and this is known as the *limiting friction*, or *limiting tical friction*.

Once the block has begun to move forward, we shall probably ice a sudden slight slackening in the pull of the spring ance, perhaps to 36 gm. Thus, though a pull of 36 gm. s not sufficient to set the block in motion, once it *is* in tion this pull is sufficient to keep it moving. The force uired to keep a body moving is a measure of what is called

the *kinetic* or *sliding* friction, and from what has been sa
we see that it is somewhat less than limiting statical frictio

Explorers in polar regions may find it very difficult to g
a sledge to move, but once it has started it is not so hard t
keep it moving. In the first case they have to exert a for
great enough to overcome statical friction; in the secon
only the smaller force required to overcome sliding frictic
is needed.

Laws of friction. From common experience we know th
the force required to drag a load along a level floor has to b
increased if the load is increased. Is the force *proportion*
to the load?

We can answer this question by the help of a spring balanc
but better results can be obtained by using a pulley and balan
pan as follows.

A wooden block is attached to a scale-pan by a thread passing over a pulley [1] as shown in Fig. 9/2. The weight of the scale-pan (nearest gram) is first found. Weights are then placed in it until the block just begins

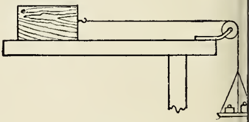


FIG. 9/2

to move. Increasing loads are placed on the block, and th
minimum force required to produce motion is observed i
each case. The results may be set out as follows:—

Wt. of block and added load (R).	Force required to move block etc. (F).	$\frac{F}{R}$

R stands for 'normal reaction,' i.e. the reaction betwee
table and block in a direction at right angles to the surfac
in contact. In this case it is equal to the total weight.

[1] In practice it will be found convenient to use the inclined pla
(*Junior Physics*, p. 38) lying horizontally, instead of the actual tab
top, the pulley of course remaining attached to the plane.

ill be noticed that F/R is approximately constant, i.e. *the niting friction is proportional to the normal reaction.*

Now turn the block on to one of its narrow faces, and repeat e experiment, using the same loads as before. We find at we obtain the same values for F, i.e. *the friction is independent of the area of the surfaces in contact.*

We have a practical illustration of both these laws in the se of the rim brake of a bicycle. The braking effect is, of urse, due to the friction between the brake-shoes and the n. By gripping the brake-lever more tightly we increase e normal reaction,[1] and the friction in proportion.

We do *not* increase the braking effect, however, by increasing e size of the brake-shoes—though, by way of compensation, rge shoes would not wear out so quickly as small ones.

Coefficient of friction. The experiment of p. 88 showed that r a given pair of substances the ratio F/R is constant. This tio, often denoted by the Greek letter μ (mu), is called the **efficient of friction.**[2] Its value for wood on wood (dry) from 0·25 to 0·50, while if the wood is soaped it is about 20. For metal on metal (dry) it is between 0·15 and 0·20, t this may be reduced by oiling to 0·05 or less—a point interest to cyclists.

Rolling friction. A cart in hilly country is sometimes fitted th a 'skid brake.'

The wheel is now locked. It slides instead of rolling, and e braking effect is very marked. The driver is making e of the fact that sliding friction is greater than rolling ction. For iron wheels rolling on iron rails the coicient of friction may be as little as 1/100th part of the coicient of sliding friction.

You may wonder why there should be any friction at all such a case. The fact is that however firmly the rail may

[1] When considering the experiment of the wooden block and scalen, the reader may have thought that 'weight' would be a simpler m than 'normal reaction.' The latter term is necessary, however, as to cover cases in which (as in the bicycle brake) friction is not due nply to weight.

[2] Strictly speaking, coefficient of *statical* friction, because in our periment we found the force F necessary to start the block into tion (from rest). The force necessary to keep it moving, when ce started, would be somewhat less, as already mentioned. Calling s F′, F′/R would be the coefficient of *sliding* friction.

be laid, it always 'gives' a little, as the wheel passes over i (Fig. 9/3, where the effect is purposely exaggerated). Thu the wheel has to ascend the little hill AB, and in fact a unending series of such little hills.

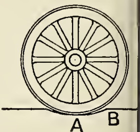


Fig. 9/3

In machinery of all sorts it commonly happens that one surface is revolving in contact with another. A simple example is the socket of a cart wheel revolving about the end of the axle. Here we have sliding friction. We may arrange, however —in the bicycle wheel for instance—to have a layer of steel balls between the two surfaces, as in the illustration on the left. The balls ro round between the two surfaces, and we have rolling frictio instead of sliding friction, the device being known as 'ba bearings.' One often sees horse-drawn milk-carts, etc., i which the wheels and axle (sliding friction) have been re

By courtesy of the Hoffmann Manufacturing Co., L

Ball Bearings and Roller Bearings

moved and replaced with the wheels of an old motor-ca (rolling friction). Such a vehicle is not only much quiete but can be pulled with a great deal less effort.

For heavier machinery, such as a motor lorry, roller bearing may be used, instead of ball bearings. Some of the mos up-to-date trains have been fitted in this way.

Questions

1. What do you mean by *friction*? Give three everyday amples.

2. Supposing friction ceased to act, what differences would u notice in carrying out the following operations: (*a*) walking; nailing up a packing-box; (*c*) digging a sand-pit by the sea-ore; (*d*) rubbing your hands together on a cold morning to ke them warm; (*e*) striking a match?

3. Explain the meaning of *coefficient of friction*.
In the experiment described on p. 88 the rectangular wooden ock weighed 360 gm. and the scale-pan 20 gm. When a 100 gm. ight was placed in the scale-pan the block was just able to ve uniformly. What value does this give for the coefficient sliding friction?
If weights totalling (i) 90 gm., (ii) 150 gm. were placed on the ock, what weights would have to be placed on the empty le-pan to maintain uniform motion?

4. Explain what you understand by *friction*, and describe ry briefly the experiments you would perform to illustrate the vs of sliding friction.
Why is it more dangerous to apply the brakes of a car suddenly en it is on a slippery surface than when it is on a rough surface?
Camb.

CHAPTER 10

PRESSURE IN LIQUIDS AND GASES

A. Liquids

THERE have been many cases in which a vessel carryi valuable cargo, perhaps including gold bullion, has sunk deep water, say 1000 ft. or more. As a rule the cargo in su a case is a total loss, while if the vessel had sunk in shall water it would soon have been recovered by divers. T point is, of course, that a diver can stand only a limited amou of pressure—and pressure increases with depth. Our earli work has taught us that it also increases with the density the liquid, the exact amount (in gm. per sq. cm.) being giv by the product hs, where h = depth below surface (in cn and s = specific gravity of liquid. Usually, however, the is a pressure *at* the surface—that of the atmosphere—a this must be added. If π gm. per sq. cm. is the pressure the surface, the pressure at depth h becomes $\pi + hs$ (Fig. 10/

In the case of water, $s = 1$, and the pressures just giv become h and $\pi + h$, respectively.

Further, we learnt that the pressure acts equally in directions, and that the *resultant* pressure is at right angles any surface in contact with the liquid. Thus, when water squirting out of a leaky hose-pipe, each escaping jet is at rig angles to the surface of the tube at that point.

We saw that increase of pressure with depth has ma practical consequences. It is closely connected with t distribution of water from a town reservoir, and with t formation of artesian wells. It also enters into a multitu of subjects, such as the diving bell, the diver's dress and t submarine.

Here is a numerical problem related to the subject und discussion.

Example **1.** *A Spanish diver off Cape Finisterre has worked at a ...th of 182 ft. Calculate the pressure in lb. per sq. in. (Atmospheric ...ssure = 15 lb. per sq. in.; 1 cu. ft. of sea-water weighs 65 lb.)*

...he chief difficulty here is that of *units*, sq. ft. instead of sq. ... and so on.

...t will be best to think of a cylinder of sea-water 1 sq. ft. in ...ss-section placed as shown in Fig. 10/2, i.e. its upper end is ...he surface and its lower end 182 ft. below.

...olume of cylinder of water = 182 cu. ft.

∴ weight = 182 × 65 lb.

...his weight is pressing on 1 sq. ft.

$$\therefore \text{ pressure in lb. per sq. in.} = \frac{182 \times 65}{144} = 82{\cdot}1.$$

To this must be added the pressure of the atmosphere, giving a total pressure of 82·1 + 15 = **97·1 lb. per sq. in.**

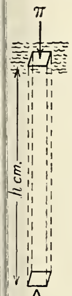


FIG. 10/1

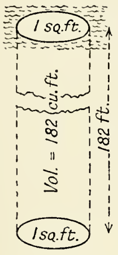


FIG. 10/2

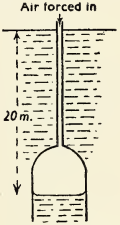


FIG. 10/3

Example **2.** *The free surface of water in a diving bell is 20 ...res below the surface of the sea. The atmospheric pressure is ...cm. of mercury. What will be the height of a barometer in the ...ing bell? (Sp. gr. of mercury is 13·6 and of sea-water is 1·025.)*

*Camb.**

...f. Fig.10/3. 20 m. = 2000 cm.

...ressure at this depth (omitting atmospheric pressure)

= *hs* gm. per sq. cm. = 2000 × 1·025 = 2050 gm. per sq. cm.

...e must add the atmospheric pressure in gm. per sq. cm.

...ow, the height of a barometer is the same whatever the bore ...he tube, so for convenience suppose the bore to be 1 sq. cm.

...hen barometer contains 75 × 1 = 75 c.c. of mercury.

...t. of this = 75 × 13·6 = 1020 gm., and all this is pressing ...n on 1 sq. cm.

...e. barometric pressure = 1020 gm. per sq. cm.

∴ total pressure in diving bell = 2050 + 1020 = 3070 gm. ... sq. cm.

Our problem is now:—If a barometer is 75 cm. high when th
pressure is 1020 gm. per sq. cm., what is its height when th
pressure is 3070 gm.?

$$\text{Required height} = 75 \times \frac{3070}{1020} = \mathbf{225{\cdot}7\ cm.}$$

Pressure at a point. A point has no area, and as pressure i force *per unit area*, it may seem strange to speak of pressu at a point. We get over the difficulty by considering a extremely small area including the point in question, an we then define ***pressure at a point*** as *the pressure on an extremely small area surrounding that point.* (Cf. velocity at a given instant, p. 4.)

Specific gravity by U-tube. On p. 77 of *Junior Physics* we considered a 'U-tube' method of finding specific gravity (Fig. 10/4). BFD is mercury, AB is the liquid whose specific gravity is being found (say alcohol), an CD is water, the quantity being so adjusted that B and D ar at the same level. If AB is h_a cm. and CD is h_w cm., it can b shown that the required specific gravity is $h_w \div h_a$.

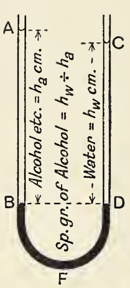


FIG. 10/4

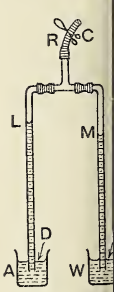


FIG. 10/5

For the reason already given in our earlier book, the U-tub method is not very accurate. Much better results are obtaine by using apparatus similar to that designed early in the 19t century by Robert Hare, who was Professor of Chemistry i the University of Philadelphia.

Fig. 10/5 represents a determination of the specific gravit of alcohol, contained in the beaker A, while water is containe in W. The liquids are sucked up at C, after which the clip closed. The specific gravity is equal to *height of water colum* (EM) ÷ *height of alcohol column* (DL).

Ieasuring gas pressure. For measuring small pressures h as that of the domestic gas supply, a U-tube containing ter or oil may be used. The gas is con-ted as shown in Fig. 10/6, and the ght h is measured. The required pres-e is that experienced at A, and this is, of rse, equal to the product hs, where s is specific gravity of the liquid used.

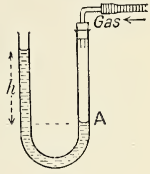


FIG. 10/6

'he siphon. Suppose the tube ACDB in . 10/7 is full of water. The water will lently move if the pressure in one ection is greater than that in the other.

Tow, if P = atmospheric pressure, the upward pressure A is $P - x$ (where x is the pressure due to the column of iid AC).

imilarly, upward pressure at B is $P - y$.

$\therefore$ (pressure at A) $-$ (pressure at B) $= (P - x) - (P - y)$
$$= y - x.$$

'hus the pressure at A, tending to drive the liquid from to right, is greater than that at B, tending to drive it n right to left; and so the liquid will flow from left to right.

Vhen, owing to the transfer of iid, both quantities are at the ie level (L and M), $y - x = 0$. pressure in the two directions is n equal, and liquid ceases to flow.

Totice that if x exceeds the ght of a barometer made of the iid in question (34 ft. in the e of water), the connecting tube not remain full, and there will io siphon action.

'o sum up, the conditions for ion action are (see Fig. 10/7):

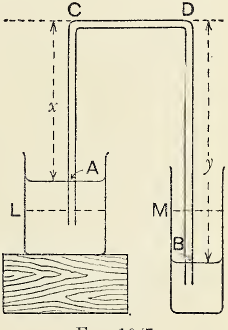


FIG. 10/7

(i) Tube ACDB must be full of iid.

ii) Height CA must not exceed the height of a barometer made of the liquid in question.

ii) B (i.e. surface of liquid in receiving vessel) must be at a lower level than A (surface in supplying vessel).

A siphon is often used for emptying a vessel which cann conveniently be tipped up, or for removing an upper lay of liquid when it is desired to leave the lower layer undisturbe

In a common type of lavatory flush the exit pipe is cover by a heavy iron bell. On raising this and allowing it to fa water is pushed into the exit pipe, causing a siphon acti to set in which continues until the tank is empty.

The tank is filled from the inflow pipe T, which is open and closed by the movement of a lever, operated by t floating ball B.

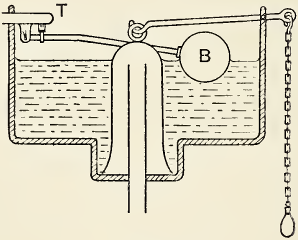


FIG. 10/8

Transmission of pressure. In Fig. 10/9 A is a cylinder of cro section, say, 100 sq. in. connected by a pipe C with a mu narrower cylinder B, of cross-section say 1 sq. in. Cylinders a pipe are completely full of water, A is closed at the top by t disc E, and B by the plunger D. Suppose we apply a dow ward force of 5 lb.wt. to the plunger, what will be the eff on E, the upper surface of A?

Pressure is transmitted equally in all directions throu a fluid, and therefore E will experience the same pressure th was applied to B—viz. 5 lb. per sq. in. But E has an ar of 100 sq. in., and so it will experience a total thrust $100 \times 5 = 500$ lb.wt.

Let us suppose the cylindrical sides of A are continu upwards as shown by the dotted lines until they are terminat by the fixed cover FG. Let E have an up-and-down slidi movement. By pressing D with a given force we can m

ing 100 times that force to bear on E, and so we can compress any object placed between E and FG.

Now, suppose that D is pushed down 1 ft. E rises only $_{10}$th ft., because, though the volume of water entering A is qual to that leaving B, it has to spread itself over 100 times e area. We therefore have (if the force applied to A is lb.wt.)—

$$\textit{work put into machine} = 5 \times 1 = 5 \text{ ft.lb.}$$
$$\textit{work got out of machine} = 500 \times \tfrac{1}{100} = 5 \text{ ft.lb.}$$

an example of the Principle of Work.

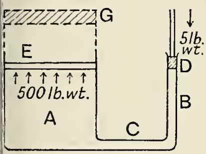


Fig. 10/9

The mechanical advantage of the ideal machine is, of course, $500 \div 5 = 100$.

Our machine as indicated so far is a somewhat theoretical arrangement, but a few improvements soon suggest themselves. We need a valve in the pipe C, so that, though water can be pushed from B to A, none can flow ck. Again, when we draw D back in preparation for another ish, it will be necessary that B should fill up with water from valve-controlled inlet. These and other modifications were ade by the Yorkshireman Joseph Bramah in 1795, the achine in its final form being known as the *Bramah Press* or

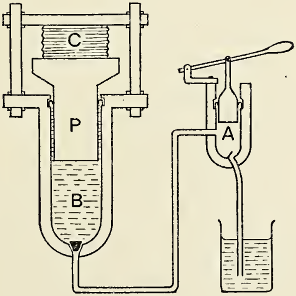
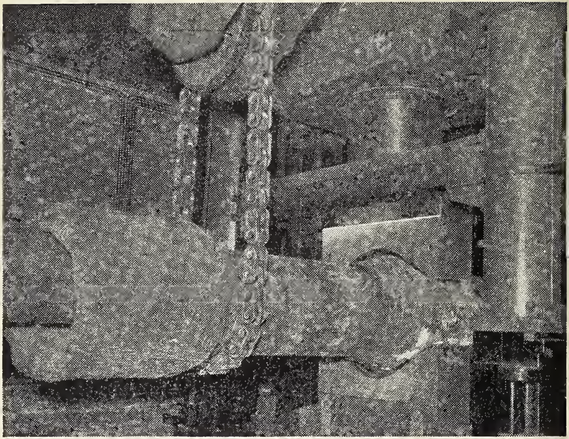


Fig. 10/10



By courtesy of English Steel Corporation, Ltd.

ELECTRO-HYDRAULIC PRESS AT WORK

hydraulic press. Fig. 10/10 will give a fair idea of its gener[...] construction, though many details are omitted.

One of the inventor's difficulties was that when pressure was being applied, water tended to escape past the pistons. If he tried to avoid this by making the pistons fit very tightly, it became nearly impossible to move them. He got over this finally by making a groove in the cylinder, into which fitted a circular leather band, folded over so that [...] section was the shape of an inverted U. We can see that [...] the cylinder advances, water will be pushed into this '[...] making the movable flap press hard against the cylinder a[...] so completely preventing escape of water.

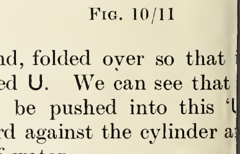


FIG. 10/11

The Bramah Press is used for compressing bales of cott[...]

ieezing oil out of seeds, shaping steel ingots and many ier purposes. The press in the illustration is being used forge the end of a boiler drum, which it is squeezing with orce of 7000 tons weight.

'he *hydraulic jack* used for raising motor-cars is very ilar in principle to the press just described, but it is operated h oil instead of water. In Fig. 10/10 we must imagine car to be in the position C, the frame round which has n removed.

'he cylinders A and B are connected by an additional not present in the ordinary hydraulic press, and so not wn in the figure. This pipe includes a tap, and when we h to lower the car we open the tap, whereupon oil flows k into the small cylinder, and the piston P falls.

B. Gases

Iere we shall take up and extend, quite briefly, the chief its with which we dealt in our earlier book.

Ve saw there that the pressure of the atmosphere is isured by the barometer, and we referred to a 'rather ous defect' commonly found in this instrument. Let us what this is. Suppose our instrument is as shown in 10/12, the surface of the mercury in the tube being at and that of the mercury in the dish at D. CD is the ght of the barometer,' and the scale by which we measure height should have its '0' mark at D.

ow, suppose the mercury rises owing to an increase in isure. More mercury in the tube means less in the dish, he level of D falls. Hence to get a true reading we should e to lower our scale slightly. This is much too inconvenient practice, and we have to content ourselves with an in-irate reading.

o get over the difficulty, the mercury reservoir is made to sist of a wash-leather bag, the bottom of which can be ed up or down by turning a screw (Fig. 10/13). This is e until the mercury surface just makes contact with the it of an ivory pin, and it is then in the correct zero position. r its inventor, this form of the instrument is known as the

Fortin barometer. It is nearly always fitted with a vern scale, so that a more exact reading can be taken. This sc (PQ, Fig. 10/13) can be moved up or down by turning screw S. This is done until its base is level with the surf of the mercury, and the reading is then taken. In Fig. 10 it would be 29·37 in.[1]

It is worth while noting that in meteorological m

Fig. 10/12

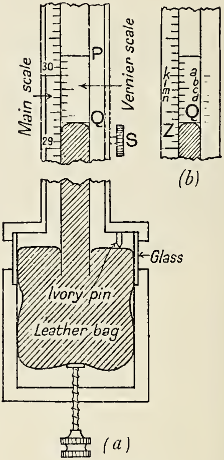


Fig. 10/13

pressure is expressed not in inches or centimetres of mercu but in *millibars.* (A millibar = 1/1000th of a bar, whic a pressure of 10^6 dynes per sq. cm.)

[1] The vernier scale PQ is 9/10ths of an inch long, and is divided i 10 equal parts, so that the length of each part is $9/10 \div 10$, or 9/10 of an inch.

To read the vernier, we find that division of it which coincides most nearly coincides) with a 'main scale' division. In Fig. 10/ this is a, which coincides with k. Now, since $ab = 9$ hundredth an inch, while $kl = 10$ hundredths (one-tenth), it is clear that $bl =$ hundredth, or 0·01. Similarly, $cm = 0{\cdot}02$, $dn = 0{\cdot}03$, and so Working down in this way, we find that $QZ = 0{\cdot}07$. Thus the requ reading is $29{\cdot}3 + 0{\cdot}07 = 29{\cdot}37$ in.

xample 3. If the relative density of mercury = 13·6, *and* 1 *gm.* = 981 *dynes, express 'normal pressure'* (76 *cm.*) *in millibars.*

s the height of the barometer is the same whatever the cross-ion, suppose the latter to be 1 sq. cm. You should now ble to go on for yourself. The answer is **1014.**

et us briefly recall ***Boyle's Law***, which states that *If a in mass of gas is kept at constant temperature, its volume vary inversely as the pressure.*

ig. 10/14 shows a convenient form of appa-s by which it may be demonstrated. The ain mass of gas' is enclosed in the part CD, the pressure is the atmospheric pressure (as n by the barometer) *plus* or *minus* the rence between the levels at D and E.

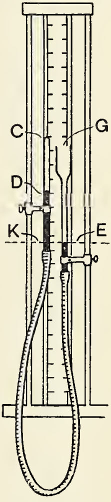


FIG. 10/14

Q. Which is it—plus or minus—in the figure ?]

xample 4. A strong glass tube 30 *cm. long closed at one end is lowered to the sea-bottom end downwards, and then drawn up. By a ical method it is found that the sea-water must filled the tube to within* 1 *cm. of the closed end. the depth of the sea at this point, assuming the temperature is the same as at the surface. ospheric pressure* = 76 *cm. of mercury. Den-of mercury* = 13·6 *gm. per c.c., and of sea-* 1·02 *gm. per c.c.*)

nsity of mercury : density of sea-water = : 1·02.

a barometer made of sea-water would have ght of $76 \times \frac{13 \cdot 6}{1 \cdot 02}$ cm. = 1013 cm.

w, the air in the tube has been compressed to 1/30th of olume.

it has been under a pressure of 30 atmospheres.

t air pressure on sea surface accounts for 1 atmosphere.

sea-water accounts for 29 atmospheres.

produce 1 atmosphere pressure, we need 1013 cm. of sea-.

for 29 atmospheres we need 1013 × 29 cm. = **294 metres.**

use of pressure in gases. Suppose a man A is holding a iron plate in front of himself, while another man B

hurls golf balls at him. He would feel the arrival of each as a single sharp blow. If B obtained a number of assista A would, of course, feel a quick succession of sharp blows.

Suppose B were able to get so many assistants that shield was receiving 40 or 50 blows per second. This frequ is so great that A would no longer be able to distinguish separate blows, but he would feel a fairly steady *pres* against his shield.

Now, a great deal of evidence points to the fact that a such as air is not 'all in one piece,' but consists of an enorm number of rapidly moving particles called molecules, t being separated from one another quite as definitely as golf ball (in the volley of golf balls) is separated from anot Small as these molecules are, a great deal is known al their size, speed, etc. Thus the number present in 1 cu. of air at N.T.P. (i.e. at 0° C. and a pressure of 76 cm $2 \cdot 7 \times 10^{19}$. That does not convey very much, so let us a rough idea in another way. The population of the w is somewhere about 2000 millions. If the $2 \cdot 7 \times 10^{19}$ m cules were replaced by pound notes, there would be m than enough to give 2000 million pound notes to every of the 2000 million people on the surface of the earth.

The molecules are continually flying about, continu hitting one another and rebounding, each molecule colli some millions of times per second with its companions. speed of these flying particles is very variable, but in the of air at ordinary temperature it is not far short of the sp of a rifle bullet. (Air is a mixture of nitrogen molecules oxygen molecules, with smaller numbers of some others.)

Naturally these molecules are continually hitting the s of the containing vessel and then rebounding. It is very rapid succession of impacts that produces pressu much as it was produced by the rain of golf balls in illustration.

Now let us crowd these millions of molecules into a sm space—we did this in our 'Boyle's Law' experiment, by mal the mercury rise in the closed limb of the tube (*Junior Phy* p. 100). They will now hit the sides of the vessel much m frequently, and therefore the pressure will be increased. mathematicians can prove that if a gas is made up of m

es, as just described, the pressure ought to vary inversely the volume. This is, of course, exactly what we found in r experiment.

[f you have a dented ping-pong ball and warm it in front the fire, it straightens out, owing to an increase in the ernal pressure. What has happened from the molecular nt of view?

[he application of heat has increased the speed of the lecules, and they now pound the inner surface of the ping-ıg ball with greater force—i.e. greater pressure is exerted. us in the statement of Boyle's Law it is always specified t the temperature must be constant; otherwise we should e a change of pressure, even if the volume remained stant.

Questions

A

. By how much would the pressure at a point 20 cm. below surface of mercury exceed that at the surface? (Sp. gr. of cury = 13·6).

. Using Hare's apparatus with water and alcohol, the water ımn is found to be 16·6 in. high and the alcohol column 20 in. d the sp. gr. of alcohol.

. In some experiments to find the specific gravity of paraffin by means of Hare's apparatus, the following results were ained :—

. of water column (cm.) .	25·0	30·0	35·0	40·0	45·0	50·0
. of oil column (cm.) . .	31·0	37·0	44·0	49·8	55·9	62·4

l the specific gravity in each case, and also obtain the average. rk to 3 significant figures throughout.)

Find the pressure in lb. per sq. in. at the bottom of a lake ft. deep. (1 cu. ft. of water weighs 62·3 lb.; atmospheric sure 14·7 lb. per sq. in.)

A cylindrical tank of 'static' water is 9 ft. deep, and the of the base is 1120 sq. ft. Find (i) the pressure at a point he bottom in lb. per sq. ft., (ii) the total thrust on the bottom ons. Assume that 1 cu. ft. of water weighs 62·4 lb., and ect atmospheric pressure.

B

1. The Dead Sea has a maximum depth of 1284 ft. Wh would be the pressure in lb. per sq. in. at this depth, given th the mean specific gravity of the water is 1·17? What would the pressure at this depth in fresh water? (Neglect atmosphe pressure. 1 cu. ft. of fresh water weighs 62·4 lb.)

2. Calculate the total thrust on a square plate of side 12 c immersed horizontally 20 cm. below the surface of a liquid density 0·8 gm. per c.c.

3. Find the thrust exerted on the bottom of a vessel of unifo cross-section 50 sq. cm. by water which fills it to a depth 20 cm. Find the additional thrust on the bottom of the ves when a cubical block of wood of volume 50 c.c. and sp. gr. = floats freely on the surface. *O.C.**

4. A cubical tank of 1 metre edge is filled with water. Wha the resultant thrust on the base and in what units is it measur *O.C.**

5. A tank of 'static' water is 40 ft. long, 20 ft. broad and 4 deep. Calculate the total thrust on (*a*) the bottom of the ta (*b*) one of the shorter sides. (The mass of 1 cu. ft. of water 62·5 lb.) *Lond.**

[*Hint.* Find the *average* pressure on the side, i.e. the press at a depth of 2 ft., and then multiply by the area to obtain total thrust.]

6. Calculate the total thrust on a square plate of side 10 immersed horizontally 15 cm. below the surface of a liquid density 0·8 gm. per c.c. *O.C.**

7. Describe a method you would employ to measure the pr sure of the gas supply in the laboratory.

If the gas pressure is read as 5 in. of water, while the barom reads 30 in. of mercury, calculate the total pressure of the in lb.wt. per sq. in. (Specific gravity of mercury = 13·6, 1 cu. ft. of water weighs 62·4 lb.) *C.W.B.*

8. Describe and explain fully the action of the siphon transferring a liquid from one vessel to another.

Two cylindrical beakers of the same height, but of cr sectional areas 30 and 100 sq. cm. respectively, stand side side on a table. The small beaker is filled with water, and larger one is empty. What fraction of the water will it be possi to transfer from the smaller to the larger beaker by means siphon? *Camb.*

9. The larger piston of a hydraulic press is 12 in. in diame and the smaller piston $\frac{1}{2}$ in. in diameter. What force will larger piston exert when the smaller has an effort of 30 lb. applied to it? *Lond.**

0. In a hydraulic press, the diameter of the larger plunger is ·m. and the diameter of the pump plunger is 5 cm. Calculate force exerted by the ram when a force of 2 kgm.wt. is applied he smaller plunger. *O.C.**

1. Describe and explain the action of a Fortin barometer. at errors will be introduced (*a*) if the barometer is not vertical, f the mercury is damp? *O.C.**

2. Explain what is meant by atmospheric pressure, and cribe an instrument by which it can be measured. Indicate the reading of a mercury barometer is independent of the s-sectional area of the column.

vertical barometer tube 100 cm. in length, and dipping into cury, contains a small quantity of air. When the open end 5 cm. below the surface of the mercury, the meniscus is 30 cm. n the upper closed end. When the tube is pushed into the cury so that the open end is 35 cm. below the surface, the iscus is 20 cm. from the closed end. Calculate the atmospheric sure. *O.C.*

3. Some dry air is enclosed by a pellet of mercury 10 cm. in th in a uniform capillary tube, which is sealed at one end open to the atmosphere at the other end. When the tube aced vertically with the open end uppermost, the length of air column is 13·3 cm. When the tube is inverted so that the ed end is uppermost, the length of the air column is 17 cm. ulate the pressure of the atmosphere. *Camb.**

. A barometer contains some air above the mercury column in consequence reads 72 cm. when the true barometric pres- is 75 cm. of mercury. The top of the tube is 82 cm. above mercury in the trough. What is the true pressure when the ing is 68 cm., the tube being adjusted so that the top is still m. above the mercury in the trough? *Dur.**

. Calculate the atmospheric pressure in dynes per sq. cm. n the mercury barometer stands at 77 cm. (Sp. gr. of ury = 13·6, and $g = 981$ cm./sec.^{2})

. Calculate the pressure in *bars* if the barometric height is mm. of mercury. (Density of mercury = 13·6 gm. per c.c.; 981 cm./sec.^{2})

CHAPTER 11

THE PRINCIPLE OF ARCHIMEDES (RESUMED)

THE ancient Greeks pursued scientific studies to a co siderable extent, but were not much given to exact measu ment. As a result, they often went wrong when deali with a question in which *quantity* was involved. We h seen, for instance, that they believed (quite wrongly) th the rate at which a body falls to the ground is proportio to its weight.

The 'Principle of Archimedes' is an exception, proba because it can be arrived at simply by *thinking*—and Greeks were great thinkers. In Chapters 10 and 11 of earlier book we have already dealt with it at some leng In the present chapter we shall concern ourselves for the m part with some of its more difficult applications.

The Principle may be stated thus: *If a body is partly completely surrounded by a fluid, it will experience an upth equal to the weight of fluid it is displacing.*

Comparing this statement with that given on p. 108 of earlier book, two differences will be noticed. (i) The insert of the words 'partly or completely.' This is done to incl the case of floating bodies. (ii) The word 'fluid' has b used instead of 'liquid.' This term (Lat. *fluere* = to fl includes gases as well as liquids, for we shall see prese that the Principle holds for gases. Thus the statement given above may be regarded as the Principle of Archime in its most general form.

In the earlier book we saw that by weighing a body in and then in water we could find its specific gravity. Le now consider the more awkward case that arises when substance is soluble in water—a crystal of rock-salt instance.

Here we must choose some liquid in which the substa is insoluble. In the case mentioned, turpentine may used. The method will be clear from an example.

Example 1. *A piece of rock salt weighs* 13·24 *gm. in air, and* ·75 *gm. in turpentine of specific gravity* 0·90. *Find the specific* *avity of the rock-salt.*

Wt. in air	13·24 gm.
,, ,, turpentine	7·75 ,,
∴ Loss of wt.	5·49 ,,

∴ wt. of turpentine displaced $= 5{\cdot}49$ gm.

But sp. gr. of turpentine $= 0{\cdot}90$

∴ vol. of turpentine displaced $= \dfrac{5{\cdot}49}{0{\cdot}9} = 6{\cdot}10$ c.c.

∴ vol. of rock salt $= 6{\cdot}10$ c.c.

But wt. of rock salt $= 13{\cdot}24$ gm.

∴ sp. gr. ,, ,, $= \dfrac{13{\cdot}24}{6{\cdot}10} = 2{\cdot}17.$

N.B. (i) If the specific gravity of the liquid is not given must be found, e.g. by use of the density bottle.

(ii) In some cases the most suitable liquid is a saturated lution of the given solid. In this, of course, the solid is soluble.

Specific gravity of floating body. We can also find the ecific gravity of a small floating body, e.g. a cork, by means the Principle of Archimedes. A suitable 'sinker' is obtained ass stopper, piece of lead, etc.) and we then find (i) weight cork in air, (ii) weight of sinker in air, (iii) weight of sinker water, (iv) weight of cork + sinker in water. The result worked out as shown below.

Example 2. *A piece of cork weighs* 1·48 *gm. It is attached to a* *gm. brass wt. and the combination weighs* 13·18 *gm. in water.* *e brass weight alone weighs* 17·62 *gm. in water. Find the specific* *vity of the cork.*

The volume of a body in c.c. is numerically equal to the 'loss wt.' (in water) in grams (*Junior Physics*, p. 111).

∴ Vol. of brass weight $= 20 - 17{\cdot}62 = 2{\cdot}38$ c.c.

Again,

wt. of brass + cork, in air $= 20 + 1{\cdot}48 = 21{\cdot}48$ gm.

wt. of brass + cork, in water $= 13{\cdot}18$ gm.

∴ vol. of brass + cork $= 8{\cdot}30$ c.c.

But vol. of brass $= 2{\cdot}38$ c.c.

∴ vol. of cork $= 5{\cdot}92$

∴ sp. gr. of cork $= \dfrac{\text{wt.}}{\text{vol.}} = \dfrac{1{\cdot}48}{5{\cdot}92} = \mathbf{0{\cdot}25}.$

Principle applied to floating body. You will remember th apparatus by which we weighed a body in water—balance small wooden stool, etc. (Fig. 11/1).

Now if we were to weigh a cork, piece of wood, etc., in thi way the cotton by which we were suspending it would b slack, and the 'weight in water' would be zero. Therefore i the case of a floating body, the *loss* of weight, or upthrust would be (wt. in air) − (wt. in water) = (wt. in air) − zer
= wt. in air.

In short, for a floating body, loss of wt. = wt. in air.

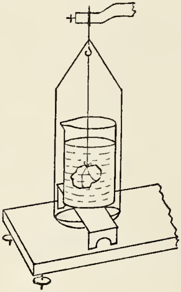


Fig. 11/1

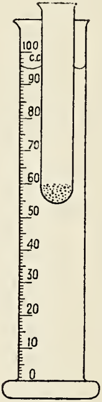


Fig. 11/2

Thus the statement 'loss of weight equals weight of liqu displaced' becomes 'the weight of a floating body is equal the weight of liquid displaced.' This statement is oft known as the Principle of Flotation. It is really a speci case of the Principle of Archimedes—the Principle applied floating bodies.

It is worth while recalling how we tested the truth of t Principle of Flotation by experiment. As our floating bo we took a test-tube containing some sand or lead shot, a weighed it. We then floated it in water contained in measuring cylinder (Fig. 11/2), and by taking the reading bef

was put in, from the reading afterwards, we found the ume of water displaced, in cubic centimetres, which, of irse, gave the *weight* of water displaced, in grams. This found to be equal to the weight of the floating body. Here fairly difficult example which involves this principle.

Example 3. *A rectangular wooden raft measuring 2 m. × 1·5 m. × m. is being used for salvaging lead from a damaged vessel. It ecided to take as the 'maximum safe load' half the weight of lead would just produce submergence of both raft and lead. If the ific gravity of the wood is 0·7, of lead 11·4, and of sea-water , find the maximum safe load.*

n this problem it will be best to work in cubic decimetres. 1. dm. of water (1000 c.c.) weighs 1000 gm. = 1 kgm.

ol. of raft = 20 × 15 × 3 cu. dm.
= 900 cu. dm.
wt. = 900 × 0·7 = 630 kg.

ippose wt. of lead required for complete submergence = x kgm.

ol. of lead = $\frac{x}{11 \cdot 4}$ cu. dm.

otal vol. of raft and lead = $900 + \frac{x}{11 \cdot 4}$ cu. dm.

hen just on the point of submerging, vol. of sea-water dis-ed = $900 + \frac{x}{11 \cdot 4}$ cu. dm.

wt. of sea-water displaced = $\left(900 + \frac{x}{11 \cdot 4}\right) \times 1 \cdot 03$ kgm.

it this = wt. of floating body (raft + lead)

$$\left(900 + \frac{x}{11 \cdot 4}\right) 1 \cdot 03 = 630 + x.$$

lving, we get $x = 361 \cdot 3$ kgm.

'maximum safe load' = $\frac{1}{2}$ of 361·3 = **180·6 kgm.**

lloons and airships. Applying the Principle of Archimedes ie case of a body such as a balloon surrounded by air, ee that the upthrust should be equal to the weight of lisplaced. A proof of this is given on pp. 107–8 of our er book, except that the brass weight mentioned there be replaced by a balloon, the liquid being replaced by Here we will give a very brief résumé of the proof.

nagine A to be held captive by a rope BC (Fig. 11/3). e is tension in the rope indicating an upthrust from the

surrounding air (the upper air is pressing downwards a D_1, D_2, D_3, etc., and the lower air is pressing upwards a E_1, E_2, E_3, etc. The 'E's predominate because pressure greater as we come nearer to the earth; hence the resultar pressure is upwards.)

How great is this upthrust?

If the balloon disappeared and its place were taken by th air that was originally in that position, the latter would mov neither upwards nor downwards. But this air obvious

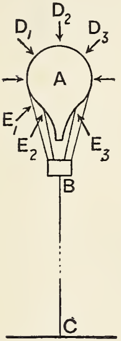


Fig. 11/3

has *weight*, which in the absence of oth forces would cause it to move downwar Therefore the outside forces acting on it ar on balance,[1] equal to this weight, and a acting upwards.

These outside forces are just the sar whether the space A is occupied by air or the balloon. The balloon therefore is subj to an upward force equal to the weight of a which it displaces.

It is now easy to see why a balloon rises it is filled with some light gas such as hydr gen. Suppose the hydrogen weighs 1 cw and an equal volume of air weighs $14\frac{1}{2}$ cw Suppose also that the envelope of the ballo ballast, basket, etc., together weigh 4 cw The total weight (allowing for the hydrogen 5 cwt. The upthrust is $14\frac{1}{2}$ cwt. Therefore the lifting pov of the balloon would be $9\frac{1}{2}$ cwt.

It is worth while repeating this calculation for helium (wh is non-inflammable). Helium is twice as dense as hydrog and so would weigh 2 cwt. The lifting power comes out $8\frac{1}{2}$ cwt.—not so very much less than before. The ch objection to helium is its comparative rarity, for the o considerable supplies are found in certain oil-wells of United States. America will not sell the gas to fore countries, because she knows that airships may be used other purposes than those of peaceful transport.

[1] I.e. allowing for the fact that some of the forces act from ab downwards, but are more than balanced by those acting from be upwards.

The barrage balloon, all too familiar during the war, is made th a double skin. It is filled with hydrogen, but under the se there is a scoop through which air can be admitted into e space between the two skins. When the balloon is freshly ed with hydrogen, these are pressed together and all the is squeezed out. As it rises into gions of lower pressure the hydro- n expands, the surplus escaping rough a valve into the atmosphere. hen brought to lower altitudes the reased pressure would cause the lloon to be rather floppy and shape- s, but this is prevented by the ry of air through the scoop.

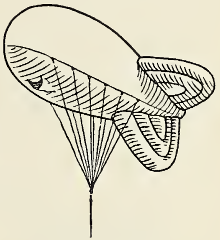
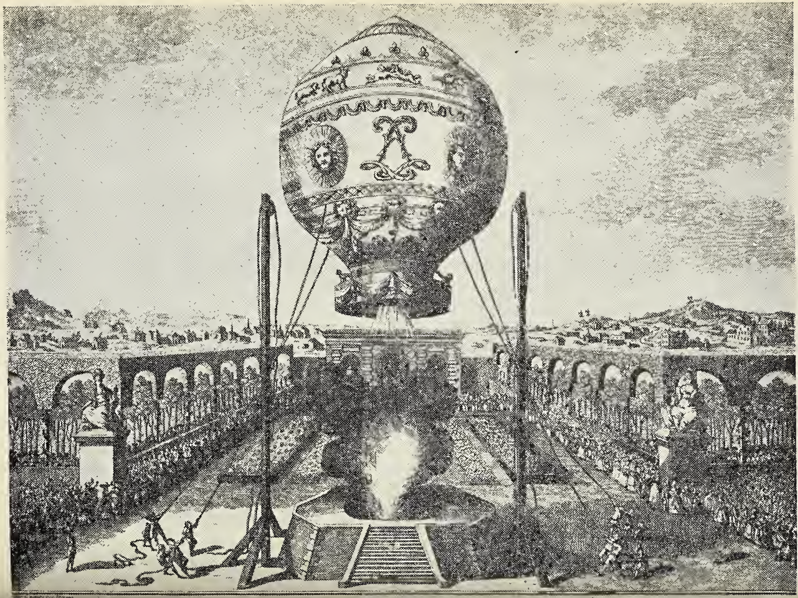


FIG. 11/4

The fins at the rear serve to keep balloon pointing into the wind. ey are filled with air, which enters ough scoops.

Historical Note. Even in the most remote ages, man watched birds and dreamed of a day when he, too, would be able fly through the air. Quite naturally he always thought wings attached to his own body, and records of some very ious attempts at flight have been preserved. Thus early the 16th century an Italian alchemist undertook to fly n the walls of Stirling Castle to France, and actually made attempt, but was immediately in need of treatment for roken leg. It appears that his wings, though made chiefly eagles' feathers, which would naturally soar into the vens, contained some derived from the ordinary hen, ch tended to move downwards towards the dunghill. At t, that was the explanation put forward by the unfortunate iemist.

or real advance we must wait for the year 1783. The thers Montgolfier had often noticed how clouds floated in air, and they thought that if only they could enclose e cloud-like substance in a bag, the bag ought to float. most promising substance seemed to be smoke, so they erimented with a paper balloon with an open neck at the tom, holding it over a smoky fire for some time, and then asing it. We are not surprised that the experiment was



VUE ET PERSPECTIVE DU JARDIN DE Mr. REVEILLON FABRIQUANT DE PAPIER.

essful, for of course the balloon would be filled with hot which is less dense than cold air. In June 1783 they gave eat public demonstration, filling a linen globe 105 ft. in mference with smoke from a fire fed with bundles of ped straw. When the balloon was released it soon rose great height, and after a 10 minutes' flight descended at nt $1\frac{1}{2}$ miles away. It was a great triumph!

fore the year was out men were actually making ascents re balloons,' carrying a brazier of hot coals just under eck of the balloon and adding fuel as required. At the time, however, successful attempts were being made to alloons with hydrogen, and in December 1783 Dr. Charles[1] a successful ascent in a balloon with a suspended car, substantially different from those with which we are iar to-day. He ascended from the Tuileries, remained ome time at an elevation of 2000 ft., and descended two s later at a little town 27 miles away. Three months a balloonist succeeded in crossing the channel from and to France.

out 1850 men began trying to devise some means of ng a 'dirigible' balloon (Fr. *diriger* = to direct), but it not until the first year of the present century that any antial success was achieved—actually by Count Zeppelin. progress has been made, but there have been some le disasters which serve as a reminder that many problems emain to be solved.

Questions

A

'ill in the blanks in the following table:—

bstance.	Wt. in air (gm.).	Wt. in water (gm.).	Vol. of body (c.c.).	Sp. gr.
er . .	35·80	31·80	......	......
le . .	16·08	......	6·00	......
. .	22·70	......	......	11·35
. .	......	6·08	4·00	......
inium .	......	......	5·21	2·70

[1] The discoverer of Charles' Law ('Heat,' p. 154).

2. A flat-bottomed test-tube, containing lead shot to mak float vertically, sinks to a depth of 4·6 in. in water, 4 in. in b and 5·5 in. in methylated spirit. Find the specific gravit brine and of methylated spirit.

3. To what depth would the test-tube of q. 2 sink in (i) par oil, sp. gr. 0·80, (ii) sulphuric acid, sp. gr. 1·84, and (iii) glyce sp. gr. 1·26.

B

1. State *Archimedes' Principle* and explain how it is ap to find the specific gravity of a solid.

A piece of glass weighs 25 gm. in air, 15 gm. in water and 17 in paraffin oil. A lump of copper sulphate weighs 16 gm. in and 10 gm. in paraffin oil. Calculate the specific gravitie paraffin oil and copper sulphate. *Lond.*

2. Define *specific gravity*. Describe a method of finding specific gravity of a piece of cork.

A barge 120 ft. long and 20 ft. broad, whose sides are vert floats partially loaded in water. How many inches will it when 12·5 tons of cargo are added? (1 cu. ft. of water we 62·5 lb.) *Lond.*

3. A body (sp. gr. = 0·94) is fastened by a thread to bottom of a vessel containing brine of sp. gr. = 1·04, so that body is completely immersed in the liquid. Given that tension in the thread is 2 gm.wt., find the volume of the b *O.C*

4. A cubical block of density 1·5 gm. per c.c. and weig 96 gm. in air is suspended by a string so that it is comple submerged in a liquid of sp. gr. 0·75. What will be the ten in the string?

If the upper surface of the block is coated with cork of den 0·5 gm. per c.c. so that it floats with the upper surface of cork in the surface of the liquid, what thickness of cork wi required? *O.C.**

5. A body which sinks in water is suspended from a sp balance and gradually lowered into water. State and exp the difference in the readings when the body is (*a*) just above water surface, (*b*) partly submerged, (*c*) just wholly submer (*d*) a few inches below the surface. How could informa obtained from these readings be used to find the specific gra of the body?

What mass of copper wire must be wrapped round a pie wax of mass 20 gm. and specific gravity 0·89, so that the will just sink in water? (Specific gravity of copper is *Bri*

6. Explain as fully as you can why an inflated rubber di is able to float with several men on board. State in ge terms the physical principle involved.

A flying-boat rests on the surface of the sea and takes on a load petrol. Find the additional volume of the hull submerged en it has received 150 cu. ft. of petrol of specific gravity 0·8. e specific gravity of sea-water is 1·03. *J.M.B.*

'. State the principle of Achimedes, and describe how you uld verify it by experiment.

An airship has a gas capacity of 1,000,000 cu. ft. and weighs 000 lb. when deflated. Calculate the force which is required prevent it from rising when it is inflated with hydrogen.

1 cu. ft. of air weighs 0·076 lb.; 1 cu. ft. of hydrogen weighs 053 lb.) *Camb.*

. A cork ball on one pan of a beam balance is balanced by ss weights on the other pan. A bell-jar which can be evacuated an air-pump is placed over the balance and sealed. Describe l explain what you would expect to observe as the air is dually removed from the jar.

You are given a tangle of bare copper wire. Describe in detail v you would determine the specific gravity of the copper and length of the wire without unravelling it. *Dur.*

. Describe a hydrometer for measuring the specific gravity of quid and illustrate by a diagram showing the scale graduations. tate the principle involved in its action.

uniform glass tube provided with a loaded bulb at its lower has a mass of 50 gm. It floats vertically in water with 8 cm. stem exposed, and in a liquid of specific gravity 1·25 with cm. exposed. Calculate the area of cross-section of the e. *Lond.*

0. A solid wooden sphere of radius 6 cm. and specific gravity is tied to the bottom of a vessel containing water by a string, that the sphere is completely immersed. Calculate in dynes tension in the string. What fraction of the volume of the ere remains immersed if the string is cut and the sphere floats ly? *O.C.*

CHAPTER 12

SURFACE TENSION. VISCOSITY. OSMOTIC PRESSUR

A LARGE part of the present chapter will deal with wh
seem like contradictions to conclusions previously reache
We shall find, for instance, that (provided we do not take t
much of it) solid steel may float on water, and that in certa
cases water may flow uphill! These points, and others, w
arise in connection with Surface Tension. Later in th
chapter we shall be concerned with two other subjec
Viscosity and Osmosis. All three, strictly speaking, belo
to a separate branch of Physics known as *Properties of Matt*

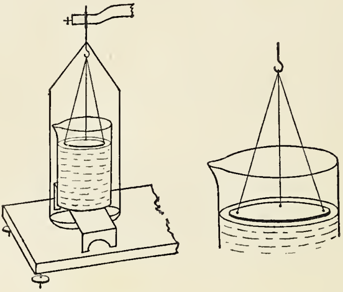


FIG. 12/1 (*a*) FIG. 12/1 (*b*)

and it is only as a matter of convenience that they have be
put at the end of our 'Mechanics and Hydrostatics' section.

We will begin with a simple experiment in which a cle
glass cover-plate is attached by means of wax to three pie
of thread. These are tied together at their upper ends a
hung from the hook of a balance. Weights are placed in t
other pan so as just to counterpoise the arrangement.

A beaker of water rests on a balance stool (as in spec
gravity experiments), the amount of water being so adjus
that the plate just touches the surface. On raising the le

the balance the plate is found to 'stick,' and the force with hich it sticks is measured by the extra weights that have to placed in the other pan to cause the plate to break away.

The under side of the plate is then found to be *wet*, showing at the extra weights were required not to separate glass om water, but to separate water from water. *The force th which parts of the same substance cling together is known* ***cohesion.***

If the experiment is repeated with mercury, the glass plate found to come away *dry*, showing that mercury clings to rcury with more force than it clings to glass. *The force th which one substance clings to a different substance is known* ***adhesion.*** Thus we speak of the adsive force between glass and mercury.

It has already been explained (p. 102) at substances are believed to be comsed of extremely minute particles led molecules, and the experiments t mentioned prove that molecules ract one another, that the attracn of water molecules for glass molees is greater than that of water lecules for one another; and that attraction of mercury molecules glass molecules is less than that mercury molecules for one another.

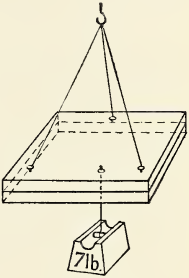


FIG. 12/2

t is evidently the force of cohesion which holds the different ts of a body together and causes it to resist 'breaking.' s a force operating between a molecule and its neighbours, l acts only through extremely small distances. If it were erwise, we could instantly repair broken crockery by ssing the separated parts together.

f care has been taken to make the surfaces of two slabs lass very accurately plane, and these are pressed together, siderable force is required to separate them (Fig. 12/2)— surfaces are so close that the force of cohesion is able to ne into play. When we repair broken articles with glue, nent, etc., we are evidently making use of the force of *ad*hen. You can think out for yourself the reason why such subnces have always to be applied when wet, or at least plastic.

Surface Tension. Think of a drop of water or other liqui The molecules of which it is composed are all attracting on another, and so we should expect the drop to take the mo compact form possible, which is a *sphere*.

Actually there are other forces—notably that of gravity- to consider in addition to the force of cohesion. The resul is that the shape is not as a rule truly spherical. In the cas of very small drops, however, the force of gravity is sligh in comparison with that of cohesion, and the shape is ver nearly spherical.

When drops of liquid (water, for instance) are lying on surface such as a table-top, the force of *adhesion* is prominen and causes the drops to be non-spherical. It is true th very small drops of mercury lying on a table are spherical; bu in this case adhesion is small in comparison with cohesio (as shown by the experiment of p. 117), and as the drops ar very small, the force of gravity is slight.

Allowing for all disturbing factors, we may say that drop of liquid tends to assume a spherical shape. It behav as though it were covered with a thin elastic skin. Of cour no such skin actually exists. What *does* exist is a force attraction between one molecule and another. In wh follows we shall usually employ the 'elastic skin' idea, becau the effects that would be produced by such a skin are exactl the same as those produced by the attractive forces betwee molecules. The force produced by such an imaginary ski is known as **surface tension,** and may be defined as *a for at the surface of a liquid producing effec similar to those that would be caused if th surface consisted of a thin elastic mem brane, but really due to the attractive forc which the molecules of the liquid exe upon each other.*

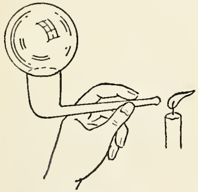


Fig. 12/3

Practical Effects. Surface tension perhaps most obviously seen in a soa bubble. When one is blown on the en of a pipe, the surface tension causes con traction, and it is actually possible to blow out a candle flam by means of the air thus expelled (Fig. 12/3).

The steel of which a needle is made has a specific gravit

nearly 8. Yet a needle if laid gently down on water will ıt, supported by the surface tension. . 12/4 shows an end-on view of the ting needle.

FIG. 12/4

The material of which an umbrella is de is porous, and yet it does not let the water through. e threads are connected by a film of water, the tension of ch is sufficient to resist penetration by the drops constantly ing on it. It is for the same reason that a tent gives tection against rain, and most campers are acquainted h the unfortunate results that follow if the film is broken prodding.

nsects such as the water boatman are often seen 'skating' the surface of water. They are, of course, supported by face tension.

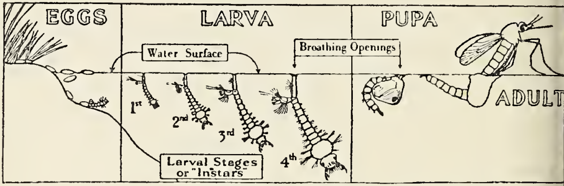
t is not surprising to find that surface tension varies greatly between one liquid and another. Thus the surface tension vater is greatly reduced by dissolving soap in it, and that hy a gardener so often adds soap to the liquid with which s syringing rose-bushes, etc. High surface tension causes er to collect in little balls on the surface of the leaves (this asily observed after a slight shower). The soap solution ı its low surface tension spreads over the whole of the leaf, so pests such as green-fly, etc., can be effectively dealt ı.

ot water has a lower surface tension than cold. Hence if match-sticks are floated on water, parallel and about an ı apart, and if the liquid between them is touched with a wire, the match-sticks spring away from one another. same thing happens if a drop of soap solution is placed the water between the sticks. These results also you ıld be able to explain.

ou have very likely read that malaria, which has been the se of untold thousands of deaths in various parts of the ld, is spread by certain mosquitoes, and so by killing the quito the disease is checked.

he mosquito lays its eggs on the surface of water, and e hatch out into *larvae*. The latter swim about under the ace, and by means of gills obtain some air from the water—not enough. They find it necessary to come to the surface

from time to time to rest and breathe, and they hang hea downwards from the surface by means of a breathing tul which passes through the tail (Fig. 12/5), their weight bei supported by surface tension.



By courtesy of the Director British Mosquito Control Institut

FIG. 12/5

By treating the water with paraffin a thin oil film is forme with a much lower surface tension than that of wat Hence the larvae find it nearly impossible to support the selves, and many of them drown.

The survivors develop into pupae, and from these the ful developed mosquitoes emerge. In the process, however, t mosquito is once again dependent on surfa tension, and the presence of paraffin preve this last essential change.

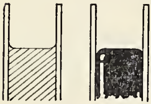


FIG. 12/6

When water touches glass the surfa curves upwards (Fig. 12/6a). You mu often have noticed this in a burette measuring jar. In the case of mercury t curve is downwards (Fig. 12/6b). It can proved that these effects are due to surface tension, and shall take them for granted in the course of the next paragra

Capillarity. Suppose we put a very narrow tube into wat We may suppose that at first the water 'finds its own lev (Fig. 12/7a—for clearness the width of the tube is grea exaggerated), but the surface takes the curved form indicat Think of a stretched skin lying along this curve. The mid portion will evidently be pulled up to the level of the t edges (Fig. 12/7b), and then the edges will once more cu upwards (Fig. 12/7c). Once again the middle portion will pulled up (Fig. 12/7d), and so on. The process will stop wh

: upward force due to surface tension is balanced by the vnward force due to the weight of the column of liquid. : should expect that the thinner we make the tube the her would be the column of liquid supported; and this ound to be the case.

n the case of mercury, surface tension would pull the umn of liquid *downwards* to a point at which the upward ssure due to the higher level of the liquid outside the tube g. 12/8) is balanced by the downward force due to surface sion.

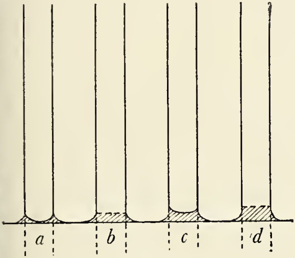


Fig. 12/7

Fig. 12/8

'arrow tubes such as are used for showing these effects urface tension are called capillary tubes (Lat. *capillus* = a ·), and the phenomenon itself is known as capillarity. ances of capillarity are extremely common in daily life.

Ve have an example in the soaking up of ink by blotting-er, the pores in the paper serving as capillary tubes, and ery similar instance is seen when the corner of a lump of ar is dipped into tea. An example with a very practical ring is the continuous rising of oil in the wick of a lamp.

ardeners sometimes quote a sort of proverb, 'the hoe is best watering can.' The air spaces between grains of form irregular capillary tubes, up which water rises from w, and when it reaches the surface, evaporation takes e. In dry weather it is desirable to check this evaporation, he gardener gets to work with his hoe. As a result, the er can now rise only to the level at which the broken und begins, some inches short of the surface.

Viscosity. Many liquids such as water, petrol and alcoh are 'thin' or limpid, i.e. they pour easily. Others such treacle and lubricating oil are sticky or viscous, and can on be poured slowly. Viscosity is due to internal frictio Instead of one portion of a liquid slipping easily over anoth it passes over it with difficulty.

It is wrong to suppose that some liquids are viscous a others not. All liquids possess some degree of viscosity— is only a question of more or less. The following experime will enable us to make a rough comparison of the viscosi of various liquids—say water, olive oil, methylated spi and syrup (made by adding two or three parts of water to o of golden syrup).

A tube about 12 in. × $\frac{1}{2}$ in. internal diameter may be us closed at one end.[1] It is *nearly* filled with the liquid to examined, and corked—a fair-siz bubble of air being left betwe liquid and cork. It is then invert and the time required for the bub of air to rise from the bottom of t tube to the top is noted. In a v viscous liquid such as olive oil t movement is extremely slow.

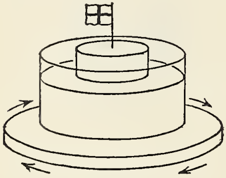


Fig. 12/9

Another experiment to sh that even a 'thin' liquid su as water possesses viscosity is described by Prof. Fleming his 'Waves and Ripples.' A glass vessel half full of wate placed on a revolving table. Floating in the water is a rou wooden disc carrying a paper flag mounted on a wire (Fig. 12/

When the table is turned slowly the disc is at first affected. The glass vessel is, so to speak, slipping past water contained in it. By and by, however, the flag be to turn in the same direction as the table, and before lo the glass vessel, water and disc are all moving round like solid mass.

The experiment just described shows that there is a defin amount of friction between the outer layer of water and containing vessel, and also between successive layers of wa

[1] *Open* tubes of these dimensions are often used for combus experiments in chemistry and if corked up will serve very well.

man rowing on a river often makes use of this fact. Near e banks the current is weaker because of the friction offered the banks and the bottom (the stream being shallower ar the edge). Hence if he is rowing upstream he keeps near e edge, while if going downstream he keeps near the centre, as to have the full advantage of the current.

Osmosis. In Fig. 12/10 a thistle funnel is shown with a piece pig's bladder tied round it at A. It is surrounded by water a beaker. Enough copper sulphate solution is poured o the funnel to bring the level up to C, that of the water tside.

On leaving the arrangement for some hours, it is found t the level of the copper sulphate solution steadily rises Fig. 12/10 it has risen to the point B). How we to explain this?

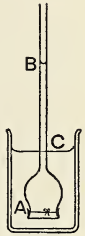


Fig. 12/10

First of all, the membrane at A is what is known *semi-permeable*, i.e. it will allow water to pass ough it, but will not allow the passage of a solid solved substance, in this case copper sulphate. acts as a sort of sieve.

This being the case, it looks as though water uld pass quite freely from the beaker into the stle funnel, and from the thistle funnel into the ker. We imagine the dissolved substance as a t of 'extra,' unable itself to pass through, but ering no opposition to the passage of the water in which s dissolved.

But it is clear from the experimental result that water is sing *into* the funnel more freely than it is passing *out*. y is it, when the liquid has reached a position such as B the thistle funnel, higher than the level C in the beaker, t it does not drop till the level is the same on both sides?

Clearly it must be supported by pressure from below, and s pressure can only arise from the fact that copper sulphate present in solution. We call it the *osmotic pressure* of the ution. Given a perfect semi-permeable membrane, liquid continue to rise in the thistle funnel until the downward ssure due to the column of liquid is equal to the osmotic ssure of the solution.

n many ways osmotic pressure closely resembles gas

pressure. Indeed, it has been shown that, in general, x gra of a substance dissolved in v c.c. of water exert an osmot pressure equal to the gaseous pressure that would be exert if x grams of that substance were present as a gas with volume adjusted to v c.c.; and there are other close analog between osmotic pressure and gas pressure.

However, to go fully into these questions is rather beyo the scope of this book. Let us return to our copper sulph experiment and summarise one or two practical conclusions.

First, the substance dissolved need not have been cop sulphate. We could have used sugar, common salt, or a other soluble substance. Similarly, there is a great cho of semi-permeable membranes.

Another point is that we need not have had pure wa on one side of the membrane. We could have used cop sulphate solution on both sides, provided one solution w stronger than the other. In such a case the effect of osmo pressure is to cause water to pass from the weaker solution the stronger, thus tending to equalise their strengths.

Osmosis is very common in nature, as we shall see present and a semi-permeable membrane is often provided by t living cell walls of a plant. This may be shown by t following simple experiment.[1]

Two large potatoes are peeled, and an end is cut off e so that a flat side is presented. Each potato is then hollow out, leaving a wall about half an inch thick. One potat boiled for three or four minutes, so as to kill the cells. E potato is now supported in a bea of water by means of a knitti needle passed through the upper e and a good pinch of salt or ca sugar is placed in each. In a d or so a considerable quantity water will have passed into unboiled potato, but not into boiled one, the reason being that the live cell walls h acted as a semi-permeable membrane.

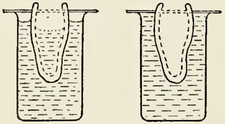


Fig. 12/11

The pressure due to osmosis is often very great. Thus pressure set up by a 1% solution of saltpetre is enough

[1] From the *School Science Review* of Oct. 1935.

pport a column of water over 100 ft. high. We begin to derstand why osmotic pressure can account for the rising the sap in trees.

Dried raisins swell when put into water. Inside the raisin solution of sugar, etc., and the skin forms a semi-permeable mbrane, through which water from outside can pass. as behave in the same way, and there are many other mples.

The action of various salts as a purgative—e.g. Epsom ts and Glauber salts—seems to depend largely on osmosis. e wall of the intestine acts as a semi-permeable membrane, l so water passes into the bowel from outside, thus serving flush it.

f a doctor is bathing a wound with salt solution he likes have the latter of $0{\cdot}9\%$ strength. The reason is that the s in contact with the nerve endings are surrounded by a ni-permeable membrane, and contain a fluid having an notic pressure equal to that of a $0{\cdot}9\%$ salt solution. Hence en in contact with such a solution the cells neither gain lose liquid. Thus there is no change in the pressure they rt on the nerve endings, and consequently no sensation smarting.

Questions

Distinguish clearly between *cohesion* and *adhesion*, and give mples of each.

Give reasons for the following:—

) A needle may be floated on water.
) Though an umbrella is made of porous material, it does not let the water through.
) A gardener often adds soap solution to a liquid which he wishes to use for spraying.

If the end of a tube of very narrow bore is dipped into er, the water rises in the tube. How do you account for ? Mention two examples in daily life in which the same ciple is at work.

It is sometimes found that 'tins' (made for containing ders such as cocoa, dried milk, etc.) hold water very well, leak when paraffin oil is put in them. Why?

ANSWERS TO NUMERICAL EXERCISES

nswers to the odd-numbered questions only have been given.

Chapter 1, p. 9

A

(i) 60; (ii) 15; (iii) 90.

B

(i) 0; (ii) 48 ft./sec. **3.** (*a*) $11\frac{1}{2}°$ N. of E.; (*b*) 1 hr. 38 min.

Chapter 2, p. 24

A

(i) 5; (ii) 0·122. **3.** (i) -32 ft./sec.^{2}; (ii) 100 ft.

B

(*a*) 1392 ft.; (*b*) $38\frac{2}{3}$ ft./sec. **3.** 100 ft.
(*a*) 17·7 sec.; (*b*) 6223 ft. **7.** 144 ft.; 6 sec.

Chapter 3, p. 35

(*a*) 1·5 cm./sec.^{2}; (*b*) 19·75 cm./sec. **3.** 25·6 ft./sec.^{2}

Chapter 4, p. 39

4 ft./sec.^{2} **5.** $\frac{Vt}{vT}$.

Chapter 5, p. 49

A

(i) 21 ft.lb.; (ii) 1680 ft.lb.; (iii) 15 ft.lb. **3.** $3\frac{1}{33}$.

B

(i) 144 f.p.s. units, 162 ft.lb.; (ii) 101·8 f.p.s. units, 81 ft.lb.
6720 ft.lb., 1·22.
39,270. **7.** (*a*) 280 lb.wt.; (*b*) 513 lb.wt.
a). (*a*) 49,000 cm. gm.; (*b*) 98,000 c.g.s. units.
b). 1127 ft./sec. **11.** (*a*) 240 ft./sec.; (*b*) 15 sec.
At ground level, P.E. = 0, K.E. = 900 ft.pdls.; at highest
t, P.E. = 900 ft.pdls., K.E. = 0; half-way up, P.E. = 450
lls., K.E. = 450 ft.pdls.

Chapter 6, p. 63

A

Lever, 50; 2; 1·98.
Block and tackle, 36; 4; 3. *Inclined plane*, 100; 0·8; 80.
3·6, 4, 90%.

B

28 lb.wt.; 4200 ft.lb. **3.** 2 ft. 6 in.
1·40, 35%; 2·40, 60%; 2·71, 67·7%; 2·80, 69·9%; 2·80, 70·0%.
(*a*) 528; (*b*) 63·1%; (*c*) 396 ft.lb.

Chapter 7, p. 75

A

1. (i) 5 lb.wt. making ∠ of 37° with greater force.
(ii) 10 gm.wt. in direction of greater force.
(iii) 50 gm.wt. in direction of original forces.
(iv) 5·2 lb.wt. bisecting ∠ between forces.
(v) 18·5 lb.wt. bisecting ∠ between forces.

B

1. 130·4 lb.wt. and 63·6 lb.wt. **3.** $3\frac{1}{4}°$ S. of E.; 8·5 lb.wt.
7. Tension in BC, 58·6 lb.wt.; in AC, 71·7 lb.wt.
9. 44·7 gm.wt., $26\frac{1}{2}°$ N. of E. **11.** 0·866 kgm., 0·500 kgm.

Chapter 8, p. 84

A

1. (i) $7\frac{1}{2}$ in.; (ii) 1·5 in. from middle point. **3.** 30 gm.

B

1. 0·732. **3.** (*a*) $2\frac{1}{2}$ lb.wt.; (*b*) $2\frac{1}{2}$ lb.wt.; (*c*) 10 ft.lb.
5. On a line joining the mid-points of the '1–2' and '3–4' si and 3 in. from the latter.
7. 4·33 lb.wt. at 20° with the vertical; 12·76 lb.wt.
9. 36 cm. from rear of fuselage; 82 gm.

Chapter 9, p. 91

3. 0·33; (i) 130 gm; (ii) 150 gm.

Chapter 10, p. 103

A

1. 272 gm./sq.cm. **3.** 0·806, 0·811, 0·795, 0·803, 0·805, 0 0·803.
5. 561·6; 280·8.

B

1. 651; 556. **3.** 1000 gm.wt.; 30 gm.wt.
5. (*a*) 200,000 lb.wt. (= 89·3 tons wt.); (*b*) 10,000 lb (= 89·3 tons wt.).
7. 14·9. **9.** 17,280 lb.wt. (= 7·714 tons wt.). **13.** 81·9 c
15. 1,027,300.

Chapter 11, p. 113

A

1. *Top line*, 4, 8·95; *2nd*, 10·08, 2·68; *3rd*, 20·70, 2·00; 10·08, 2·52; *5th*, 14·07, 8·86.
3. (i) 5·75 in.; (ii) 2·50 in.; (iii) 3·65 in.

B

1. 0·80; 2·13. **3.** 20 c.c. **5.** 2·78 gm.
7. 40,700 lb.wt. (= 18·17 tons wt.). **9.** 1·25 sq. cm.

PART II

HEAT, LIGHT AND SOUND

CHAPTER 13

HEAT AND TEMPERATURE. THERMOMETERS

Recapitulation. In Chapter 12 of *Junior Physics* we cussed the effects of heat on a body, and saw that these mainly three.

1) There is a rise of temperature.
2) The body expands.
3) There may be a change of state, from solid to liquid or from liquid to vapour.

Ve know now that to these general rules there are exceps. Thus when heat is applied to a beaker of melting there is no rise of temperature, and the same is true when heat boiling water—its temperature remains at 100° C. h regard to (2), alloys such as 'invar' have been prepared ch undergo practically no change of volume when heated, we have learnt that if water at a temperature between C. and 4° C. is heated it actually contracts.

hange of state is no doubt always produced provided the essary temperatures are available. In the sun, for instance, n metals such as iron are present in the state of vapour.

hen in the earlier book we learnt to distinguish between t and temperature. We saw that the distinction is ilar to that between *quantity* of water and *level* of water. wo barrels of water are made to communicate by means a pipe, water flows from high level to low level quite spective of the *quantity* of water in each (Fig. 13/1). In the e way, if two bodies are placed in contact, heat will flow n the body at higher to that at lower temperature. When lacksmith quenches a red-hot horse-shoe in a cistern of

water, heat flows from the horse-shoe to the water *not* becau it contains more heat (as a matter of fact it contains mu less), but because it is at a higher temperature.

Lastly, in our earlier work we saw how a thermometer is made.

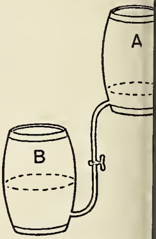


FIG. 13/1

(1) A tube is prepared by blowing a bulb on one end. Near the other end the tube is drawn out to a narrow neck and a funnel containing mercury is attached.

(2) By gently heating the bulb, some air is expelled, and on cooling, a little mercury enters. This mercury is then boiled to expel the remaining air, and on cooling, the bulb and tu are completely filled.

(3) The thermometer is now placed in a bath containi a suitable liquid, which is heated to a temperature slightly higher than the thermometer will ever be required to record. The tube is now sealed off at the neck.

(4) The lower fixed point is marked (Fig. 13/2).

(5) The higher fixed point is marked, special arrangements being made to secure that (*a*) the bulb and practically the whole stem shall be surrounded by steam and not simply by boiling water, (*b*) an outer jacket of steam shall serve to protect from draughts, etc. (Fig. 13/3).

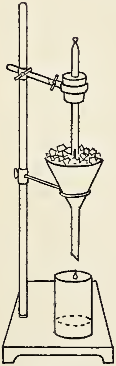


FIG. 13/2

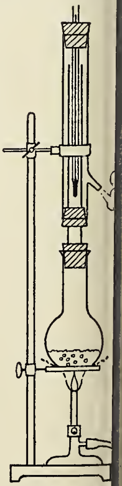


FIG. 13/3

We know now that the

nperature of boiling water depends on the pressure *mior Physics*, p. 169). In the neighbourhood of 100° C. increase of 28 mm. in the pressure raises the boiling point 1° C. Thus in accurate work it would be necessary to d the barometer and make the proper allowance. For tance, if the barometer reading were 767 ı.—i.e. 7 mm. above normal—the boiling nt would be $100\frac{1}{4}°$ C. (because 28 mm. ses the boiling point 1 degree, and 7 is a ırter of 28).

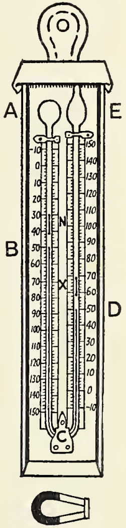


FIG. 13/4

elf-Registering Thermometers. It is often essary to know the lowest or highest temature that has been reached during a cerı interval. Thus a gardener may wish to w whether the temperature is falling so low ıis greenhouse at night that he ought to start his heating apparatus. Hence 'maximum' 'minimum' thermometers have come into There are various forms of these, but shall describe one which combines both cimum and minimum readings in a single rument.

x's Maximum and Minimum Thermometer. instrument is U-shaped, and the expanding id, consisting of alcohol, is contained in part AB. The lower part of the U is oced by mercury BCD, and covering D is a nd column of alcohol DE. The latter s only a minor part in the instrument— cures that the mercury surface at D shall ıaintained under the same conditions as that at B.

bove the mercury in each limb there is a steel index X) which just grips the glass by means of a weak spring. n the temperature is rising, the expanding alcohol ıes the mercury column BCD in front of it, and D in pushes the index X. When the temperature falls, the r end of X will evidently record the highest temperature has been reached. Similarly, the lower end of N will rd the minimum temperature. When it is necessary to t the instrument, N and X are moved into contact with

K

their respective mercury surfaces by means of a ma
net.

The instrument just described was invented by James S
about the year 1780.

The Clinical Thermometer. If a doctor were taking
patient's temperature by means of an ordinary thermometer, he would have to read it while it was still *in position*, because the moment he removed it the reading would begin to fall. He therefore uses a special form of maximum thermometer known as a *clinical thermometer*. The instrument is shown to actual size in Fig. 13/5.

The liquid used is mercury. The special feature of the instrument is that at C, a little above the bulb, the tube is bent and constricted. Now, when the bulb is placed in the patient's mouth, the mercury has no difficulty in passing C, because it is driven on by the pressure from behind, and so the temperature is accurately recorded. When the thermometer is removed, the thread of mercury breaks off at C, the upper part remaining 'stranded' and continuing to record the highest temperature reached—i.e. the temperature of the patient. To re-set the instrument it must be shaken, when the upper portion of the mercury thread passes the constriction and joins the remainder.

It is worth while to consider the features of a good clinical thermometer, and how these are secured. The features in question are: (i) *accuracy*, (ii) *sensitiveness*, i.e. there should be a perceptible movement of the thread for a very small change of temperature such as $\frac{1}{10}°$ F., (iii) *quickness of action*, (iv) *ease* in reading.

Accuracy is, of course, a matter of care in manufacture. The best clinical thermometers are not put on the market until they have been tested at the Nati
Physical Laboratory.

FIG.

Sensitiveness depends on the relation between the vol
of the bulb and the bore of the tube. A large bulb a
narrow bore both make for sensitiveness.

n an instrument which has to go into a patient's mouth s obviously not practicable to have a very *wide* bulb, but siderable volume is secured by making it *long*. The bore ery narrow, and the net result is that 1° F. is represented about $\frac{1}{5}$ in. on the stem. It is thus quite easy to take lings to $\frac{1}{10}$° F. With such an open scale the *range* is of rse quite small—usually from 95° F. to 110° F.—but this ll that the doctor requires. The temature of the human body in health is ut 98·4° F.

uickness of action. We want the whole he mercury in the bulb to reach the ent's temperature as soon as possible, until this happens the thread will inue to rise. Obviously it is necesthat all the mercury should be as as possible to the source of heat, this is favoured by having the bulb and narrow, as already mentioned. her, the glass of the bulb should be hin as is consistent with reasonable ngth.

ne quickest clinical thermometers marked 'half-minute.' Actually, a ewhat longer time than that is ed for an accurate reading. The est ones are marked '3 minutes.'

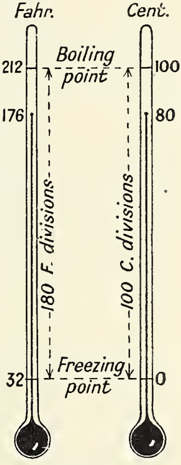


Fig. 13/6

ise in reading. The thread of meris so thin that it would not be very to take a reading, but the cylinder-shaped tube acts like nvex lens, greatly magnifying the width.

ansformation of scales. It is often necessary to transform igrade readings to Fahrenheit, and vice versa. Consider liagram (Fig. 13/6).

nis reminds us that the interval between the freezing t of water and its boiling point is 100 degrees on the igrade scale, but 180 degrees on the Fahrenheit scale.

Thus 100 C. divisions = 180 F. divisions.

1 C. division $= \frac{180}{100} = \frac{9}{5}$ F. divisions.

1 F. division $= \frac{5}{9}$ C. division

Suppose we wish to reduce a temperature of 80° C. Fahrenheit.

$$1 \text{ C. division} = \tfrac{9}{5} \text{ F. divisions.}$$
$$\therefore \quad 80 \text{ C. divisions} = \tfrac{9}{5} \times 80 = 144 \text{ F. divisions.}$$

Now 80° C. means 80 Centigrade divisions above freez point. Hence the corresponding Fahrenheit reading is Fahrenheit divisions *above freezing point.* But as freez point is itself 32° F., the required temperature must $144 + 32 =$ **176° F.**

Next suppose we have to reduce a temperature of 68° to Centigrade.

Freezing point (Fahrenheit scale) is itself 32°, so 68° F only $68 - 32$ or 36 degrees Fahrenheit *above freezing poin*

The corresponding number of Centigrade degrees ab freezing point is $\frac{5}{9} \times 36 = 20$, and as Centigrade readi are reckoned from freezing point, the answer is **20° C.**

By studying examples such as those just given, we see t the following general rules apply.

To bring Centigrade readings to Fahrenheit, multiply by $\frac{9}{5}$ *add* 32.

To bring Fahrenheit readings to Centigrade, first subtrac and then multiply by $\frac{5}{9}$.

It is a good plan to remember that 212° F. = 100° C., an notice that to get from 212 to 100, we subtract 32 and mult by $\frac{5}{9}$, while to get from 100 to 212 we multiply by $\frac{9}{5}$ (get 180), and then add 32. If you have to bring a Fahren temperature to Centigrade and are uncertain as to whe you can remember the rule correctly, ask yourself, 'I do I get from 212° F. to 100° C.?' Similarly from Centig to Fahrenheit.

Example. *At what temperature would a Fahrenheit thermom and a Centigrade thermometer give the same reading?*

Suppose the required reading is x° C. (= x° F.).
Now x° C. = $(\frac{9}{5}x + 32)$° F. by the rule given above.
But in this case the Centigrade and Fahrenheit temperat are the same.

$$\therefore \quad x = (\tfrac{9}{5}x + 32)$$
$$\therefore \quad 5x = 9x + 160$$
$$\therefore \quad x = -40.$$

Ans. **− 40° C. = − 40° F.**

Other Scales. Besides the two scales discussed above, there a third scale much used in Germany, on which the freezing int of water is marked 0° and its boiling point 80°. It was vented by a French nobleman, the Seigneur Réaumur, out 1720, and is always known as the Réaumur scale.

80 seems a curious number to have chosen, but it arose in is way. Réaumur found that 1000 volumes of diluted irits of wine (spirits diluted with one-fifth its volume of ter) expanded 80 volumes between freezing point and iling point, and it occurred to him that a very good 'degree' uld be that amount by which the temperature of 1000 lumes of this diluted spirit must be raised in order to make expand by 1 volume.

Of the three scales mentioned, the Centigrade is the simplest, d it is rather a pity that there should be any others in linary use. The multiplicity is confusing and often makes culations necessary. However, the situation might have en much worse, for J. H. Pambert writing in 1779 gives a of no less than nineteen! Sixteen of them have long since en dead and buried, and nobody mourns their loss.

Questions

A

. Express the following centigrade temperatures in degrees renheit: 100, 50, − 40, 0, 15.

. Express the following Fahrenheit temperatures in degrees tigrade: 68, 212, 113, − 40, 95.

. Construct a graph from which, for any temperature between C. and 100° C., you can read the corresponding Fahrenheit perature.

B

. The distance between the upper and lower fixed points on ermometer is 15 cm. At what height above the lower point ld the mercury stand when the temperature is 20° C.?

. You are provided with a mercury thermometer with an raduated scale. Describe how you would use it to find the perature of the room. *Lond.**

. Why would a thermometer constructed similarly to an nary laboratory thermometer be useless for taking a patient's perature? *O.C.**

Why is mercury a suitable liquid to use in a thermometer? en is alcohol to be preferred? Why is water unsuitable?

escribe a thermometer which registers both maximum and imum temperatures and explain its mode of action. *Lond.*

CHAPTER 14

EXPANSION OF SOLIDS

Recapitulation. When studying the expansion of solids our earlier book we saw first of all that a solid when hea expands only very slightly, and that rather special appara is needed to detect it. Figs. 14/1*a*, 1*b* and 14/2 will recall so of the apparatus we used.

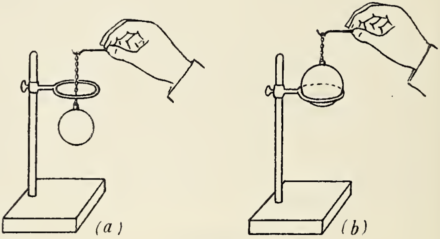


Fig. 14/1

But though the amount of expansion is very small, we that it was capable of being put to certain practical u A steel tyre can be made to fit a cart wheel very tightly making it of such a size that it can only be put on when

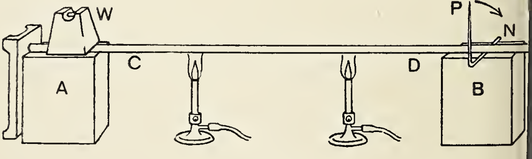


Fig. 14/2

hot. On cooling, it contracts and grips the wheel very tig indeed. This principle of 'shrinking on' is used in fixing wheel of a railway waggon on its axle. It is also use

;etting boiler plates together, the rivets being put in when
d hot and then hammered.

A glass stopper which has become set fast in a bottle may
removed by gently heating the neck of the bottle so as to
ake it expand, and then tapping the stopper.

We also considered some cases in which expansion with
ange of temperature is a source of trouble. The engineer
s to make allowance for it in building bridges, and we have
met with cases in which thick glass tumblers, jam jars,
., have been broken through pouring hot liquid into them.
Generally speaking, the thicker the glass, the more easily
it broken by unequal heating. An extreme example is
n in the new reflecting telescope at Palomar (California).
e great mirror, 200 in. in diameter, is 30 in. thick. It was
ade of Pyrex glass which has a very low coefficient of
pansion (p. 139). Even so it was necessary,
er casting the glass, to spead the cooling
ocess over a period of *ten months*!

Further Applications. The rate of a pendulum
ck is controlled by the pendulum, which swings
re slowly if its length is increased. The length
measured from the point of suspension to the
ntre of gravity of the bob.

Thus to regulate a clock which is gaining, we
ver the bob by the help of a little screw fixed
t below it. If the clock is losing we raise the
o.

FIG. 14/3

Now, if an ordinary pendulum clock has been
eping good time in the winter, it will begin to
e as the days become warmer. The reason is
vious—the length of the pendulum has increased.

There are various ways of avoiding the trouble. In some
es the pendulum bob is made to consist of a glass cylinder
two cylinders side by side) filled with mercury. Suppose
(Fig. 14/3) is the point of suspension of the pendulum
d G the c.g. of the mercury If the pendulum is always to
ng at a constant rate, the distance SG must remain con-
nt. Now with increase of temperature the rod SB becomes
ger, and this would cause SG to increase. But the same
rease of temperature causes the mercury to expand, and

therefore its c.g. G is raised, causing SG to decrease. B
properly adjusting the quantity of mercury the two opposin
tendencies may be made to cancel out, and the clock kee
excellent time.

(*Q. Would it be possible for such a clock to gain with increas temperature and vice versa? If so, how could it be put right?*)

Alloys such as 'invar' are now made which under practically no change of length[1] as the temperature vari and if these are used there is no need for the rather cost cylinder of mercury.

The rate of a watch is controlled by a balance whe

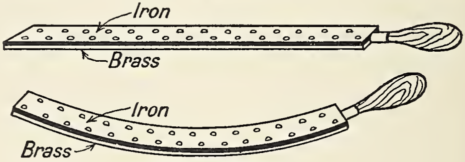


FIG. 14/4

Expansion obviously causes the weight of the rim to be mov farther from the centre, and this slows down the rate movement.

To understand the principle of compensation, we must back to the compound-bar experiment discussed in the earl book. When such a bar is heated, it bends, with the more expansible brass on the outside of the bend (Fig. 14/4).

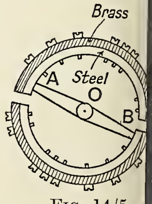


FIG. 14/5

A 'compensated' balance wheel has its rim made of two metals, brass melted on to steel, the brass being outside. The wheel has two steel spokes OA and OB in line with one another (Fig. 14/5). With rise of temperature these expand, and this of itself would throw the weight of the rim farther out from the centre. But the rise of tempe ture also causes an increased amount of bending, and t

[1] Its coefficient of expansion (see p. 139) is about $\frac{1}{11}$th that steel, and so for a very high degree of accuracy a little compensa is still required. This is secured by so arranging a small brass cylin that as it expands, it raises the bob.

ngs the weight of the rim nearer to the centre. By cortly adjusting the weight of the rim (which is done by attach- screws to it), the two effects can be made to cancel out. Q. *If a watch with such a balance wheel were found to gain hot weather, can you suggest what might be done?*)

Coefficient of Expansion. So far we have been content with h statements as that 'brass when heated expands more n iron.' We can easily see, however, that a *long* strip of n would probably expand more than a *short* strip of brass. en if we take brass and iron strips of equal length, it seems ely that an iron strip strongly heated would expand more n a brass strip only slightly heated. In fact, when we h to speak with exactness about the expansion of a subnce, we must have regard to (i) the length of the strip t is being heated, and (ii) the rise of temperature. If the gth of the strip or wire is 1 centimetre and the rise of nperature is 1° C., the increase in length is known as the *fficient of expansion.*

xample 1. *If* 1 *centimetre of iron wire expands* 0·000012 *cm.* 1° *C. rise of temperature, what would be the expansion (measured eet) of* 1 *ft. of iron wire, for the same rise of temperature?*

Suppose 1 ft. $= x$ cm.

1 cm.	for a rise of	1° C.	expands	0·000012 cm.
. x cm.	,,	,,	,,	0·000012 x cm.
. 1 ft.	,,	,,	,,	0·000012 ft.

Evidently the number representing the coefficient of ansion will be the same whether we measure the original gth in centimetres and also measure the expansion in timetres, or measure the original length in feet and the ansion in feet; and similarly for any other units, such as res or even miles. Accordingly, we define the ***coefficient expansion of a substance*** as *the increase which unit length hat substance undergoes when its temperature is raised* 1° *tigrade.*

t will be noticed that so far we have dealt only with surements of *length*. The coefficient of expansion just ned is really the coefficient of *linear* expansion, and is n so expressed. The question of the expansion of surfaces . of a sheet of copper foil) and of volume will be dealt

with presently. Evidently the term 'coefficient of lin expansion' can only be applied to a solid.

Let us now see how the coefficient of linear expansion o substance can be determined.

One method is illustrated in Fig. 14/6. The metal in t form of a tube is supported by a wooden frame, one end being fixed, while the other passes through a hole in the fra so that the tube is free to expand. Round this hole, fix to the frame, is a metal plate in the face of which three sm holes have been drilled to take the feet of a spheromet while the central screw of the latter touches a flat cap whi closes the tube at Q. The tube is wrapped round with f (not shown in the figure), and steam can be passed throu it as indicated.

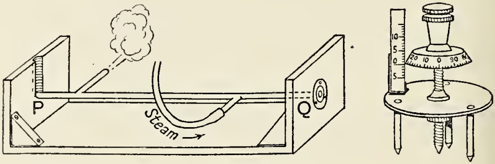


FIG. 14/6

To carry out an experiment, the spherometer is pla in position and adjusted till the central screw just touc the metal cap. The reading is then taken and the sph meter is removed. The temperature (room temperature recorded, after which steam is passed through the tube a few minutes. While it is still passing, another spherom reading is taken. To make sure that expansion is compl steam is passed for another two minutes. There shou of course, be no further change in the reading. The len of the tube is measured, and the result is then worked as follows:—

Length of tube . . . . . 80 cm.
Room temperature . . . . . 15° C.
Spherometer reading (i) 2·76 mm. (ii) 4·04 mm.
(iii) 4·04 mm.

$\therefore$ Expansion = 1·28 mm. = 0·128 cm.

Rise of temp. = 100 − 15 = 85 deg.

∴ expansion of 80 cm. for 85° = 0·128 cm.

$$\therefore \quad ,, \quad ,, \quad 1 \text{ cm.} \quad ,, \quad 1^\circ = \frac{0\cdot128}{80 \times 85} = 0\cdot0000188,$$

coefficient of linear expansion = 0·0000188

Calculations. Let us now consider one or two examples ating to coefficient of expansion.

Example 2. An engineer decides to allow for an extreme variation 70° *C. in atmospheric temperature. How much allowance uld he make for the expansion of the iron girders of the Forth dge,* 1710 *feet long?* (*Coeff. of linear expansion of iron =*)0012.)

ot of iron for a rise in temperature of 1° C. expands 0·000012 ft.

1710 feet for the same rise expand 0·000012 × 1710 ft.

1710 feet for a rise of 70° C. expand 0·000012 × 1710 × 70
= 1·436 ft. or **17·2 in.**

.B. The bridge expands in sections, each of which would e its proper proportion of this total.

Example 4. A surveyor's steel chain has a length of exactly yards at 60° *F. What will be its error if used for making surements at* 15° *F.?* (*Coefficient of linear expansion of steel =*)0012 *per deg. C.*)

he difference in temperature is 45 deg. F.

ow 9 divisions on the Fahrenheit thermometer correspond to visions on the Centigrade

. 45 divisions on the one correspond to 25 on the other.

yd. of steel, for a fall of 1 deg. C., contracts 0·000012 yd.

. 22 yd. for a fall of 25 deg. C. contract
0·000012 × 22 × 25 = 0·0726 yd.
= **2·61 in.**

.B. It was the fact that surveyor's chains were found to y appreciably in length with change of temperature, that sed scientists in the 18th century to pay attention to the ject of coefficient of expansion.

oefficient of cubical expansion. The expansion of unit *th* of a substance for a rise in temperature of 1° C. gives he coefficient of *linear* expansion. Similarly the expansion nit *volume* of a substance for this same rise of temperature s us the coefficient of *cubical* expansion. *The* ***coefficient ubical expansion of a substance*** is *the amount by which volume of that substance expands for a rise in temperature* ° *Centigrade.*

There is a simple relation between the coefficient of cubic expansion of a substance and its coefficient of linear expansion. Let us see what it is. Suppose the coefficient of linear expansion of a certain substance is l, while its coefficient of cubical expansion is c.

Fig. 14/7 represents a cube of the substance in question and each edge of the cube measures 1 unit of length.

$\therefore$ volume of cube = 1 unit of volume.

Let the temperature of the cube be raised by 1° C.

Then length of each edge increases from 1 unit to $(1 + l)$ units.

$\therefore$ volume becomes $(1 + l)^3 = 1 + 3l + 3l^2 + l^3$.

But original volume of cube was 1 unit.

$\therefore$ increase $= 3l + 3l^2 + l^3$.

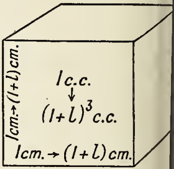


FIG. 14/7

Now because l is a very small quantity, $3l^2$ may be neglected (e.g. for steel, $l = 0{\cdot}000012$, and $3l^2 = 3 \times 0{\cdot}000012^2 = 0{\cdot}000000000432$), and l^3 is smaller sti

$\therefore$ increase $= 3l$ (practically).

But the increase in volume of this unit cube for a rise temperature of 1° C. is our coefficient of cubical expansion c.

$$\therefore \boldsymbol{c = 3l}$$

Thus *the coefficient of cubical expansion of a substance numerically equal to three times its coefficient of linear expansi*

You can easily work out for yourself the correspondi relation between the coefficient of surface expansion (s) of substance and its coefficient of linear expansion l. You w find that, numerically, $s = 2l$.

Example 5. *The temperature of a piece of copper weighing 8 grams is raised from 10° C. to 100° C. Find the increase in volu (Density of copper = 8·95 gm. per c.c. Coefficient of lin expansion = 0·000017.)*

Weight of copper = 895 gm.

$\therefore$ volume = 895 ÷ density = 895 ÷ 8·95 = 100 c.c.

Coefficient of cubical expansion = 3 × 0·000017 = 0·000051

i.e. 1 c.c. of copper for rise of 1 deg. expands 0·000051 c.c.

$\therefore$ 100 c.c. for rise of 90° expands

0·000051 × 100 × 90 = **0·459**

Why do substances expand on heating? Suppose a la floor is divided up into squares of, say, 2 ft. side. At e

int where lines intersect—points such as A, B, C, D, E, F—erson is standing, and all these people are engaged in some ;ular side-to-side exercises. Their arms and legs are ving inwards and outwards, but not very far, because of tact with neighbouring persons.

Now, suppose the order is given that this side-to-side vement is to be increased. This reires more room, and the people must n out. As a result, the total size of crowd will be greater than it was ore.

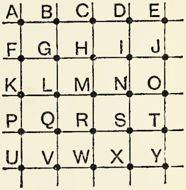


FIG. 14/8

This illustration will help us to undernd what happens when a solid subnce is heated. The extremely small ts (molecules) of which the solid is nposed have a certain regular arrangent, represented roughly by the people nding at the corners of the squares. The molecules vibrating, and this is represented by the side-to-side vement of the people.

When the substance is heated, the side-to-side movement he molecules is increased, and they need more room. The ecules 'open out,' and the result is expansion.

Questions

. Explain the term *coefficient of linear expansion*, and describe xperiment to find its value for brass.

metal ball has a diameter of 4·02 cm., and a hole in a brass e has a diameter of 4·00 cm. when both are at 20° C. To t temperature must the plate be heated so that the ball l at 20° C.) may just pass through the hole? (The coefficient near expansion of brass of 0·000018 per deg. C.) *Lond.*

If the coefficient of linear expansion of steel is 0·000012 a Centigrade degree, what will be its value for a Fahrenheit ee? If the length of a steel rail when laid at 56° F. is 30 ft., t interval must be left between the rails to allow for a rise mperature to 120° F.? *Camb.**

To what temperature must two rods of copper and iron ectively, each 100 cm. long at 15° C., be heated in order that may differ in length by 1 mm.? (The coefficients of linear nsion of copper and iron are 0·000018 and 0·000012 respecy, both per deg. C.) *Lond.**

4. Define *coefficient of linear expansion.* Give two examples practical importance in which use is made of the linear expansi of metals with temperature rise.

The length of a mercury column as read on a brass scale 76 cm., the temperature being 20° C. If the scale was graduat when the temperature was 0° C., what is the correct length the column? (Coefficient of linear expansion of brass is 0·0000 per deg. C.) *Brist.*

5. If a centimetre cube of copper at 0° C. has a mass of 8·9 gm., find its volume and density at 100° C., given that t coefficient of linear expansion of copper = 0·000017 per deg. *Camb.**

6. An iron pipe is 10 ft. long at 60° F. Calculate its leng when steam at 300° F. passes through it. (Coefficient of line expansion of iron = 0·000012 per deg. C.). *C.W.B.**

7. Two bars A and B of different metals lie parallel, side side, with two ends adjacent to each other and held rigidly the The other ends are free. The longer bar A is 150 cm. long a the coefficients of linear expansion of the bars A and B a 0·000012 and 0·000018 respectively. What must be the leng of B so that the difference in length of the bars is always the sa irrespective of temperature? *Dur.**

8. The internal volume of a sealed hollow brass cube at 0° is 1,000 c.c. and the coefficient of linear expansion of brass 0·000018 per deg. C. Find (*a*) the volume of the cube wh it is placed in an oven at 200° C., (*b*) the density of the gas insi it at this temperature if the density in the cube at 0° C. is 3·5 gm. per litre. *J.M.B.**

CHAPTER 15

EXPANSION OF LIQUIDS

the last chapter we saw how to measure the coefficient of ar expansion of a solid. We have then only to multiply result by 3 to obtain the coefficient of cubical expansion.

here is no such thing, however, as the coefficient of linear ansion of a liquid. We might put the liquid in a long tube . 15/1) and measure the length of the column AB at a ain temperature. We could then heat it to another wn temperature and measure the amount of expansion

It looks as though we might now work out the coefficient inear expansion in much the same way as, on 40, we worked out the coefficient of linear ex- sion of a metal. Why not?

FIG. 15/1

f AB were a bar of copper or other solid sub- nce and we heat it, it expands both lengthways sideways, and we can find its coefficient of linear ansion because its expansion sideways in no way cts its expansion lengthways.

he sideways expansion of the liquid, however, is sted by the walls of the containing vessel, and efore, shows itself as lengthways expansion. In BC is a measure of the *total* expansion of the id in all directions, i.e. it is a measure of the *cal* expansion, not of the linear.

he last statement requires further qualification. cannot heat the liquid without also heating the tube con- ing it. This causes the tube to expand, and so the apparent ansion BC is less than the real expansion. If BC were . and the glass tube itself has expanded 1 c.c., it is evident the *real* expansion is 10 c.c. In fact, we cannot find the unt by which the liquid has really expanded without wing that by which the containing vessel has expanded.

owever, we will leave this point for the moment, and try nd the 'coefficient of apparent expansion' of a liquid in ass vessel. Suppose we use glycerine.

Take a density bottle, see that it is dry, and then weigh (i) empty, (ii) full of glycerine. The bottle and glycerine should at room temperature, so when filling take care to hold the bottle only by the neck. There should be no air bubbles.

By means of thread, suspend the bottle in a beaker of water as shown in Fig. 15/2. This water should be at room temperature, so it will be better if the beaker has been filled some time before the lesson.

Take the temperature, heat the water to boiling point and let it continue boiling gently for five minutes. Lift out the density bottle, let it cool, wipe it dry and weigh it. The results are then worked out as follows. Suppose

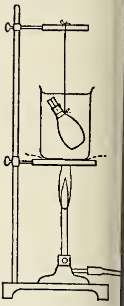


FIG. 15/2

Wt. of bottle	15·26 gm.
Bottle + glycerine before heating .	78·37
,, ,, after heating .	75·80
Initial temperature . . .	15° C.
Final temperature (assumed) .	100° C.
Wt. of glycerine left in bottle .	75·80 — 15·26 = 60·54 gm
Wt. that has escaped by expansion	78·37 — 75·80 = 2·57 gm.

Let s = sp. gr. of glycerine at 15° C.

Then *volume* of liquid left in bottle, if allowed to cool to 15° would be $\frac{60 \cdot 54}{s}$ c.c.

But at 15° C. wt. of glycerine required to fill bottle

$$= 78 \cdot 37 - 15 \cdot 26 = 63 \cdot 11$$

$$\therefore \quad \text{volume of bottle} = \frac{63 \cdot 11}{s} \text{ c.c.}$$

$$\therefore \quad \text{volume of space A (Fig. 15/3)} = \frac{63 \cdot 11}{s} - \frac{60 \cdot 54}{s} = \frac{2 \cdot 57}{s}$$

Now the glycerine left in the bottle after the experim (60·54/s c.c.) if heated once more to 100° C. would evide expand just sufficiently to fill the bottle.

i.e. $\frac{60 \cdot 54}{s}$ c.c. for rise of 85 deg. expands $\frac{2 \cdot 57}{s}$ c.c.

$\therefore$ 1 ,, ,, ,, ,, ,, $\frac{2 \cdot 57}{s} \div \frac{60 \cdot 54}{s} = \frac{2 \cdot 57}{60 \cdot 54}$ c.

$\therefore$ 1 ,, ,, 1 ,, ,, $\frac{2 \cdot 57}{60 \cdot 54 \times 85} = 0 \cdot 0004$

i.e. mean coefficient of apparent expansion of glycerine in g between 15° and 100° = **0·000496.**

N.B. (i) 'mean' coefficient, because we do not know that it s expanded *equally* for each degree of increase in temperature. e have simply taken the total expansion for 85 degrees, and vided by 85.

(ii) If asked to find the mean coefficient of expansion say tween 30° C. and 60° C., we should (before taking our first ighing of bottle + glycerine) have to leave the bottle surrounded · some time with water at 30° C., then wipe it and weigh it. terwards, of course, we should bring the temperature to 60° C. stead of 100° C., as in the experiment discussed above.

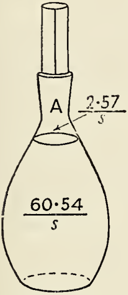


FIG. 15/3

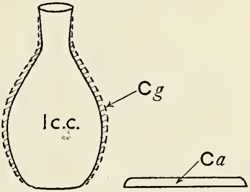


FIG. 15/4

The relation $c_r = c_a + c_g$. Imagine a bottle whose capacity xactly 1 c.c., filled with a certain liquid. The temperature raised by 1° C., and a volume of liquid will be expelled ual to c_a, where c_a is the coefficient of apparent expansion he liquid.

f the coefficient of expansion of the glass is c_g, the bottle l itself have expanded by a volume c_g for this 1° rise of nperature. Therefore the liquid must have expanded by the amount expelled) *plus* c_g (the amount required to fill extra space in the bottle), i.e. the coefficient of *real absolute* expansion of the liquid, c_r, is equal to $c_a + c_g$. may therefore write $c_r = c_a + c_g$.

Fig. 15/4 may help to give a clearer idea of the argument. e 1-c.c. bottle is exaggerated. Its expansion c_g is repreted by the shaded portion, and the expelled liquid of ume c_a is represented as piled up on the table.

L

How c_g is found. We have seen how c_a is found for glyceri
In a similar way it could be found for *mercury.*

Now, *for mercury,* the coefficient of absolute expansi c_r, has been found with great exactness to be 0·00018 Thus if we want to find c_g for the glass of a given densi bottle, we use the latter to find c_a for mercury by the meth already described for glycerine. Suppose we find th c_a is 0·000155. Then from $c_r = c_a + c_g$ we have $c_g = c_r$ $c_a = 0{\cdot}000181 - 0{\cdot}000155 = 0{\cdot}000026$.

We can now find c_r for glycerine. For we have alrea found c_a, we know c_g, and $c_r = c_a + c_g$.

So long as we keep to the same density bottle, for whi c_g is known, we can of course find c_r for any other liqu first finding c_a as already described, and then making use the relation $c_r = c_a + c_g$.

Example. *If the real coefficient of expansion of a certain liq is* 0·00138 *per deg. Centigrade, find the value per degree Fahrenh*
A flask is exactly filled by 1000 *c.c. of the liquid at* 0° *C. T coefficient of linear expansion of the glass is* 0·000004. *W volume will overflow if it is heated to* 60° *C.?*

When 1 c.c. of the liquid has its temperature raised 1° C expands by 0·00138 c.c.
For a rise of 1° F. the expansion would be only five-ninths of th
i.e. **0·00078.**

The coefficient of cubical expansion of the glass is 3 times linear $= 3 \times 0{\cdot}000004 = 0{\cdot}000012$.
The amount of liquid overflowing evidently depends on expansion *relative to the glass,* i.e. on its coefficient of *appar* expansion. This will be $c_r - c_g = 0{\cdot}00138 - 0{\cdot}000012$
$= 0{\cdot}001368$.

Thus, relative to the glass,

1 c.c. for 1 deg. expands 0·001368 c.c.

∴ 1000 ,, 60 ,, ,, $0{\cdot}001368 \times 1000 \times 60$
$= 82{\cdot}08$ c.c.

i.e. the amount overflowing will be **82·08 c.c.**

[1] A very broad indication of the method may be given. It depe on the U-tube method for finding the density of a liquid (p. 93), instead of having a column of water balanced by (say) one of alco we have a column of mercury at 0° C. balanced by another colum mercury at some definite temperature t° C. The two densities now be compared, for $d_o/d_t = h_t/h_o$, where h_t and h_o are the height the mercury columns at t° and 0° respectively. Thus d_o/d_t is fou and it can easily be shown that $d_o/d_t = 1 + c_r t$. Hence, as we kno we can calculate c_r.

Applications. The thermometer provides us with one of e most important applications of the expansion of a liquid. iother interesting application is seen in one type of *thermo-ıt.* In Fig. 15/5 a bath of liquid L is being heated, and it is sired to keep it at a constant temperature. To secure this, e lower part of a thermostat is ımersed in the liquid. The ther-ostat contains toluene, a liquid th a very high coefficient of ex-nsion.

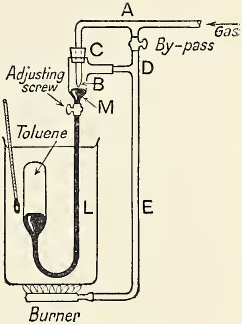


FIG. 15/5

Notice that the burner is supplied th gas by two paths: (i) the th ACBDE, and (ii) the by-pass. ıe adjustment is such that when e liquid in the bath reaches the sired temperature, the mercury, shed by the expanded toluene, st covers the tip B, so closing path ACBDE. Enough gas, wever, goes through the by-pass keep the burner alight. When temperature begins to fall, the toluene contracts, the B is uncovered, and the gas supply is reinforced.

Questions

1. When a lake freezes, why does ice first form on the surface, ile the temperature some distance below the ice is higher than freezing point? *Brist.**

2. A mercury thermometer with its fixed-point markings arated by a distance of 25 cm. has a bulb with a volume of c.c. up to the 0° C. mark. What is the mean diameter of the e of the thermometer? The coefficient of apparent expansion mercury in glass = 0·00015 per deg. C. *Lond.**

3. A specific-gravity bottle when full contains 27·5 gm. of cerine at 16° C. What weight of glycerine will be expelled en the bottle and contents are heated to 90° C.?
Coefficient of real expansion of glycerine = 0·00053 per °C.
Coefficient of linear expansion of glass = 0·0000090 per °C.)
*C.W.B.**

4. A glass flask weighs 80 gm. empty and 580 gm. when full water at 20° C. What does it weigh when full of water at C? (The apparent coefficient of expansion of water = 0·0004 ° C). *O.C.**

5. The bulb and stem of a mercury thermometer conta 0·6 c.c. of mercury when the temperature is 0° C. What is t distance between the 0° C. and the 100° C. marks if the intern diameter of the stem is 0·2 mm.? (Coefficient of appare expansion of mercury is 0·000156 per ° C.) *Brist.**

6. Distinguish between the coefficients of *real* and *appare* expansion of a liquid. What is the relation between them?

In an experiment to measure one of these coefficients, t columns of the liquid are balanced in vertical glass tubes co nected by a horizontal tube at their lower ends. The temperatu of one column is 0° C. and that of the other 100° C. The heigh of the columns are 50 cm. and 54·5 cm. Which coefficient measured by this method? Evaluate it, giving the theory your method of calculation. *Dur.*

7. The cylindrical bulb of a mercury thermometer is 2 c long and has an internal diameter of 5 mm. The diameter the stem is 0·2 mm. If the bulb is full at 0° C., what must the minimum length of the stem to measure temperatures to 110° C.? (The coefficient of real expansion of mercury 0·000184 per °C. and the coefficient of linear expansion of gl 0·0000080 per °C.) *Lond.**

8. A graduated tube contains mercury which at 0° C. occup 100 divisions. What will be the reading if the whole is rai to 100° C.? (Coefficient of absolute expansion of merc $= 1{\cdot}8 \times 10^{-4}$, coefficient of linear expansion of glass = 8 × 10

*O.C.**

CHAPTER 16

EXPANSION OF GASES

: already know that air expands when it is heated. A ited ping-pong ball, for instance, can be straightened out warming it in front of the fire. Other gases too expand en they are heated, and two questions at once suggest mselves.

1) Exactly how much does air expand when heated? In er words, what is its coefficient of expansion?

2) Have different gases different coefficients of expansion we have found to be the case with solids and liquids) or they all alike in this respect?

Ieasurement of Expansion. First we had better be quite r about the meaning of ***coefficient of expansion of air*** 'coefficient of expansion of air at constant pressure'). It *e expansion for a rise in temperature of* $1°$ *C. of a quantity ir whose volume at* $0°$ *C. is* 1 *c.c., the pressure remaining stant.*

he last four words are very important. Moderate or n great changes of pressure make no appreciable difference he volume of a solid or liquid, but we know from common erience, or from Boyle's law, that this is far from being case with a gas.

ote that the definition does not imply that the change emperature is necessarily from $0°$ C. to $1°$ C. It could be n $17°$ to $18°$, or $99°$ to $100°$, or $-25°$ to $-24°$. The it is that the quantity of air must be such that its volume ° *C.* would be 1 c.c.

arious methods are in use for finding this coefficient. he one to be described we shall use what is known as

ay's Apparatus. Here the air under examination is coned in the bulb A and in the upper part of the tube BC, h is graduated so that the exact volume can be read off. is connected with the tube DE, open to the atmosphere, also with the tube FGH, which is closed with the tap H. apparatus is filled with sulphuric acid to about B. The serves to keep the imprisoned air quite dry.

The apparatus is placed in a beaker of suitable size, an to begin with may be surrounded by water containing quantity of ice to bring the temperature to 0° C. Acid is now run out at H until the acid stands at the same level in DE and BC. As DE is open to the atmosphere, the air enclosed in A will now be at atmospheric pressure. The volume is noted, and the temperature (0° C.).

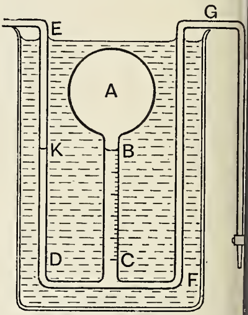


Fig. 16/1

The beaker is now heated, the water being gently stirred, till the temperature has risen 15 or 20 deg. The acid surface in the bulb tube will now be lower than in the open one, so acid is once more run out at H until the two are at the same level. The volume and temperatu are again noted. Proceeding in this way we obtain a seri of readings until, say, 80° or even 100° is reached (this la reading presents certain difficulties in practice), the pressu in every case being adjusted to atmospheric. Suppose t following results have been obtained:—

Volume (c.c.) . .	35·2	37·8	40·3	42·9	45·5	48·
Temp. (° C.) . .	0	20	40	60	80	100

Let us work out the mean coefficient of expansion betwe 0° and 100°.

35·2 c.c. for a rise of 100° expands $(48{\cdot}1 - 35{\cdot}2) = 12{\cdot}9$ c.

$\therefore$ 1 c.c. ,, ,, 1° ,, $\dfrac{12{\cdot}9}{35{\cdot}2 \times 100}$

$= 0{\cdot}00366$ or $1/273$ c

Thus the mean coefficient of expansion between th temperatures is 1/273. The results are almost exactly t same between 0° and 40°, 0° and 60°, etc.

In short, our experiment indicates that *if air is heated constant pressure, then for each increase of temperature of C. it expands by* 1/273*rd of its volume at* 0° *C.*

We may note here that if the experiment is carried out th other gases, the coefficient of expansion is still found to 1/273. Thus while different solids and different liquids ve their own special coefficients of expansion, all gases have e same—namely, 1/273.

Let us next express our results graphically.

Our 100° C. reading (volume 48·1 c.c.) is represented by point P, and our 0° C. reading (volume 35·2 c.c.) by the

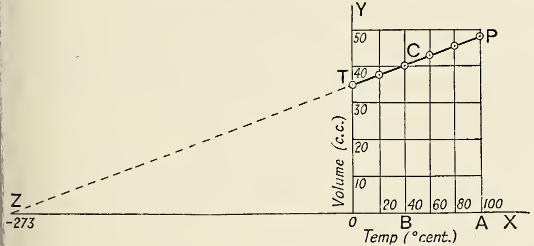


FIG. 16/2

nt T. Between these points we notice that the volume reases with almost perfect regularity (the slight deviations actually due to errors of experiment). The dotted line TZ ws what would happen *if the volume continued to decrease he same rate.* At a temperature of − 273° C. the volume ıld become nothing at all!

Ve feel that this is a rather impossible state of things, and eed it does not occur. What *does* happen is that at about 90° C. the air liquefies,[1] and with further fall of tempera- e the contraction proceeds at a much slower rate than n we were dealing with the air as a gas.

- 273° C., then, is the temperature at which the volume gas would become zero if it continued to contract at the

[1] For some time before this temperature is reached, the air is found e contracting to a greater extent than would be expected from the h.

same rate as it does when well above its temperature liquefaction. For reasons which will be mentioned later, t temperature $-273°$ C. is known as *absolute zero.* 'Absol temperature' means the number of degrees (Centigra above absolute zero. For instance, 0° C. is 273° C. ab absolute zero, and so 0° C. = 273° Absolute temperatu Similarly $-200°$ C. = 73° Absolute, because it is 73° above absolute zero, 100° C. = 373° Absolute, and so In fact, *to bring degrees centigrade to degrees absolute, add 2* Not a very hard rule!

Notice that on our graph absolute temperatures are rep sented by horizontal distances from Z. OA, for instan represents the centigrade temperature 100°, but ZA = ZO OA = 273 + 100, so ZA represents the corresponding *absol* temperature. Similarly, OB represents the centigrade te perature 40°, but ZB = ZO + OB = 273 + 40, which is corresponding absolute temperature.

Now, $\frac{AP}{ZA} = \frac{BC}{ZB}$, either from similar triangles, or fr

trigonometry (each ratio being equal to tan Z).

Hence $\frac{AP}{BC} = \frac{ZA}{ZB}$.

But AP and BC represent two volumes, while ZA and represent the corresponding absolute temperatures. He *the volumes are proportional to the absolute temperatures.*

ZA and ZB of course represent two *particular* absol temperatures (373 and 313 respectively), but the reason obviously applies to *any* two.

It has been understood throughout that the volumes measured at constant pressure. Keeping this in mind, may now re-state ***Charles' Law*** in the following form, wh should be carefully committed to memory. *If the press of a given mass of gas remains constant, its volume is proportio to its absolute temperature.*

In mathematical form, we may express this by the equat

$\frac{V_1}{V_2} = \frac{T_1}{T_2}$, where V_1 is the volume of the gas at absol

temperature T_1, and V_2 its volume at absolute temperature

Making use of the idea of absolute temperatures, calcula-ons on volume changes in gases are very easy. For instance:

Example 1. *An enclosed quantity of gas occupies* 27 *c.c. at a* *perature of* 15° *C. What would be its volume at* 87° *C., the* *ssure remaining unaltered?*

$$15^\circ \text{ C.} = (273 + 15)^\circ \text{ Abs.} = 288^\circ \text{ Abs.}$$
$$87^\circ \text{ C.} = (273 + 87)^\circ \text{ Abs.} = 360^\circ \text{ Abs.}$$

Thus in our equation, $V_1 = 27$, $V_2 = ?$ $T_1 = 288$, $T_2 = 360$.

$$\therefore \quad \frac{V_1}{V_2} = \frac{T_1}{T_2} \text{ becomes } \frac{27}{V_2} = \frac{288}{360}.$$

$$\therefore \quad V_2 = \frac{27 \times 360}{288} = \mathbf{35 \text{ c.c.}}$$

When the pressure also varies. We have just seen that arles' law tells us how the volume of a gas varies with the nperature, the *pressure* remaining constant, and that it y be expressed as $\frac{V_1}{V_2} = \frac{T_1}{T_2}$. Now Boyle's Law (p. 101) ls us how the volume of a gas varies with the pressure, *temperature* remaining constant, and is expressed mathe-tically as $P_1V_1 = P_2V_2$. *Both* laws are expressed by the ation $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$. For if the pressure is constant, $= P_2$ and the equation reduces to $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ or $\frac{V_1}{V_2} = \frac{T_1}{T_2}$, i.e. arles' Law. If the temperature is constant, we have $= T_2$ and the equation becomes $P_1V_1 = P_2V_2$, i.e. Boyle's w. In fact, the equation $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ covers all cases. us use it to solve a problem in which there is a variation h of pressure and temperature.

Example 2. *A litre of air at N.T.P.*[1] *weighs* 1·29 *gm. What* *ld it weigh at* 91° *C. and* 38 *cm. pressure?*

Let us first find what volume the air would occupy under the conditions.

[1] I.e. normal temperature and pressure (0° C. and 76 cm. pressure). etimes the letters S.T.P. (Standard Temperature and Pressure) are l instead.

$V_1 = 1$ litre, $P_1 = 76$ cm., T_1 (0° C.) = 273° Abs.
$V_2 = ?$ $P_2 = 38$ cm., T_2 (91° C.) = 91 + 273 = 364° A

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\therefore \quad \frac{76 \times 1}{273} = \frac{38 \times V_2}{364}$$

$$\therefore \quad V_2 = \frac{76 \times 364}{38 \times 273} = 2\tfrac{2}{3} \text{ litres.}$$

The weight, of course, has not changed,
i.e. $2\frac{2}{3}$ litres now weigh 1·29 gm.

$$\therefore \quad 1 \text{ litre now weighs } \frac{1{\cdot}29}{2\frac{2}{3}} = \mathbf{0{\cdot}484\ gm.}$$

We obtain a somewhat shorter solution if we realise that t density of a gas is (i) directly proportional to the pressure, (inversely proportional to the absolute temperature.

$$\therefore \quad \text{wt. of 1 litre} = 1{\cdot}29 \times \frac{38}{76} \times \frac{273}{364} = \mathbf{0{\cdot}484\ gm.}$$

Coefficient of increase of pressure. If in Lay's apparat (p. 151) the volume of the enclosed air were 273 c.c. (actua it is only about one-tenth of this amount), and we raised t temperature from 0° C. to 1° C., keeping the pressure consta the air would expand by 1/273rd of 273, i.e. by 1 c.c., and t volume would therefore become 274 c.c.

Now, keeping the temperature at 1°, let us so increase t pressure that the volume is reduced to the original 273 c If the original pressure is p_1, and the new pressure requi is p_2, we have, by applying Boyle's Law, $274 \times p_1 = 273 \times$

$$\therefore \quad p_2 = \frac{274}{273} p_1 = p_1 + \frac{1}{273} p_1$$

i.e. the pressure would have to be increased by 1/273rd of original value.

The net result is that the enclosed air has been hea from 0° to 1° *at constant volume*, and to secure this the press has had to be increased by 1/273rd of its value at 0°.

We have taken the simple case of 273 c.c. of gas hea from 0° C. to 1° C., but by applying Boyle's Law in a simi way it can be shown generally that *if an enclosed quan*

yas is heated at constant volume, then for each degree rise of perature its pressure will increase by 1/273*rd of the value it at* 0° *C.* This increase of pressure at constant volume, degree rise of temperature, expressed as a fraction of the ssure at 0° C., is known as the ***coefficient of increase of ssure at constant volume.***

'he fact that this coefficient must be equal to 1/273 has so been deduced from our knowledge that the coefficient of ansion at constant volume is also 73. But we can obtain the result by ct experiment as follows.

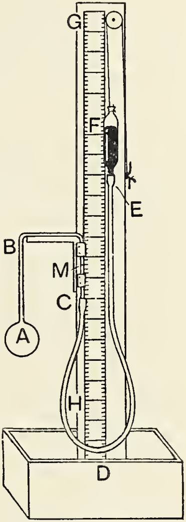


Fig. 16/3

he bulb A, 2 or 3 in. in diameter, is nected to the bent tubing BMC of er fine bore. At C this is connected 1 5 or 6 ft. of pressure tubing CDE, ninating in the mercury reservoir F. s can be clamped in any desired posi- against a vertical support, and the ht of the mercury surface can be read neans of the scale GH.

is surrounded by a vessel of crushed and after a suitable interval the re- oir is raised or lowered till the mer- stands exactly at a mark M scratched the end of the narrow tube. The sure must now be read. This is the sure of the atmosphere (as recorded he barometer) *plus* the amount by h F is higher than M. If F is below he difference between the F and M ls must, of course, be *subtracted* from barometer reading.

is now surrounded by boiling water. causes the mercury to be pushed nd M, but by raising the reservoir it rced back to that point by the in- sed pressure. The pressure is read as ady described. Consider the following results:—

Temp.	Position of F	Barometer reading	Pressure
0° C.	7·2 cm. below M	76·3 cm.	76·3 − 7·2 = 69·1
00° C.	18·1 cm. above M	76·3 cm.	76·3 + 18·1 = 94·4

The increase in pressure as the temperature is raised from to 100° is $94{\cdot}4 - 69{\cdot}1 = 25{\cdot}3$ cm.

$\therefore$ average increase per degree $= 25{\cdot}3 \div 100 = 0{\cdot}253$.

Expressed as a fraction of the pressure at 0° C. this is

$$\frac{0{\cdot}253}{69{\cdot}1} = \frac{1}{273}$$

i.e. mean coefficient of increase of pressure at constant volu between 0° C. and 100° C., is 1/273.

After taking the reading at 100° C. we could allow the surrou ing water to cool down, and take a series of temperature readin and the corresponding pressures, at intervals of 10 deg. or Working out the results we should obtain a series of values the coefficient of increase of pressure at constant volume, with careful work these would be found to be remarkably const at 1/273.

The Constant-Volume Air Thermometer. We have just s that if the temperature of the bulb of air is known, then reading the pressure we can calculate the value of the efficient. Conversely, if we assume the value of the coeffici to be 1/273, we can read the pressure and calculate the te perature. In short, the instrument can be used as a const volume air thermometer.

Suppose, for instance, we wish to find the temperatur a quantity of solid carbon dioxide. We put it in a suit vessel, crush it, and surround A with it. We adjust reservoir so that the mercury on the other side comes exa to M, and take the reading. Suppose F is 27·1 cm. belov and that the barometer reads 76·3 cm. The pressur therefore $76{\cdot}3 - 27{\cdot}1 = 49{\cdot}2$ cm. This is less than pressure at 0° C. (69·1 cm.) by $69{\cdot}1 - 49{\cdot}2 = 19{\cdot}9$ cm. Now each fall of 1° C. the pressure falls by 1/273 of the pressur 0° C., i.e. by $\frac{1}{273}$ of $69{\cdot}1 = \frac{69{\cdot}1}{273}$ cm.

But the pressure has actually fallen by 19·9 cm.

$\therefore$ no. of degrees below 0° C. is $19{\cdot}9 \div \frac{69{\cdot}1}{273} = 78{\cdot}6$

i.e. the required temperature is $-78{\cdot}6°$ C.

'e might work this out more easily by applying the ιtion $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$.

ιe 'V's' cancel, so $\frac{P_1}{T_1} = \frac{P_2}{T_2}$.

ow $P_1 = 69{\cdot}1$ cm., $T_1 = 0°$ C. $= 273°$ A., $P_2 = 49{\cdot}2$ cm.

$$\therefore \quad \frac{69{\cdot}1}{273} = \frac{49{\cdot}2}{T_2}.$$

ιis gives $T_2 = \frac{273 \times 49{\cdot}2}{69{\cdot}1} = 194{\cdot}4°$ Abs.

$$= (194{\cdot}4 - 273)° \text{ C.}$$
$$= -\ 78{\cdot}6° \text{ C. as before.}$$

lvantages and disadvantages. One great advantage of the hermometer is that it can be used for recording extremely temperatures, say down to $-\ 100°$ C. (we could use a thermometer containing hydrogen or helium instead of or even lower ranges). Equally, it can be used for very temperatures, especially if we use a bulb made of quartz; for these higher temperatures nitrogen is preferred. her advantage is its accuracy. Temperatures obtained ιe air thermometer agree exactly with those of an ideal nometer scale devised by Lord Kelvin—the 'absolute '—to which reference will be made presently.

; chief disadvantages as compared with the ordinary ury thermometer are (1) greatly increased cost, (2) the ess of finding a temperature is much more laborious, 'e cannot easily use it to find the temperature of a *small* tity of a substance.

e thermometer scale. You will remember that in making ntigrade mercury thermometer, we mark the 'lower point' by the help of melting ice and call it 0° C., and ιigher fixed point' by the use of steam, calling this 100° C. hen divide the space between the two marks into 100 l parts.

ppose we repeated the work, using sulphuric acid for hermometer liquid instead of mercury. On comparing hermometers we should find a very curious thing. At d 100° they exactly agree, of course, but at intermediate

points they differ quite considerably. For instance, w the mercury thermometer records 50° the sulphuric thermometer records only 46°. We might say, 'Well, we now exactly half-way between freezing point and boi point. The mercury has moved up just fifty divisi showing that it expands regularly. The acid has moved only forty-six divisions, showing that it does not expan much when heated from 0° to 50° as when heated from to 100°.'

That is all very well, but—*we are taking for granted the mercury thermometer is correct.* For anything we kn the sulphuric-acid thermometer may be correct, while mercury is expanding more than it should at lower t peratures, and less than it should at higher ones. Wh to decide?

Lord Kelvin in 1848 devised a thermometer scale on entirely new principle. 0° C. and 100° C. were defined in usual way with reference to melting ice and boiling w but he showed how to calculate 1/100th part of this interv i.e. how to obtain a true interval of 1° C.—*without the of any thermometric substance whatever.* Because his scale independent of any thermometric substance it was ca the ***absolute*** scale (Lat. *absolutum* = loosed from). On scale, Kelvin showed that at − 273° C. a body woul completely devoid of heat. We have met with this perature before in connection with the contraction of In fact, it is found that temperatures as recorded by th thermometer agree almost perfectly with those of the abs scale. Mercury also comes very well out of the compar Many other substances, however, including sulphuric are found to expand by unequal amounts for equal incren of temperature.

Absolute zero. We have seen that from two points of the temperature − 273° C. attracts special attention. experiments such as that described on p. 152 indicate at this temperature the volume of a gas would becom if it continued to contract at the usual rate. Second, cal tions by Kelvin show that at this temperature a subst would be completely devoid of heat.

Again, the electrical resistance of metals decreases a

perature is reduced, and in the neighbourhood of absolute —say at $-272°$ C.—it practically vanishes. An electric ent set up in a metal ring by means of magnetic induction inues to travel round and round the ring for days. gether, $-273°$ C. is a very curious temperature.

osolute zero has never been reached—probably never be—but it has been very closely approached, usually in course of experiments carried out to liquefy or solidify s. In 1895 liquid air, boiling at about $-190°$ C., was ined on a large scale by making use of the principle that a compressed gas is allowed to expand there is a fall emperature. In the same year Dewar succeeded in fying hydrogen by compressing it to 200 atmospheres, ng it with the help of liquid air to $-200°$ C., and then ing it to expand through a valve. The liquid hydrogen at $-252{\cdot}78°$. By rapid evaporation the temperature ie liquid was brought down to $-259°$, at which temure it froze. With the help of liquid hydrogen, Kamer- Onnes in 1907 cooled compressed helium to $-258°$, hen allowed it to expand. Liquid helium was obtained ng at $-268{\cdot}82°$, and by rapidly evaporating this under ed pressure a temperature of $+0{\cdot}82°$ Abs. was obtained. ially, it was noted that certain substances become ier when magnetised and cooler when demagnetised. By ng them in boiling helium while in a magnetic field and demagnetising, a temperature only $0{\cdot}0044°$ above ute zero was obtained.

iy is it impossible to have anything colder than $-273°$ C.? e molecules of which substances are composed are in movement. When a substance loses heat it loses y—heat is a form of energy—and so the average energy e *molecules* is reduced. Now, the energy of a molecule resented by the product $\frac{1}{2}mv^2$, where m is its mass and velocity (p. 45), and when this energy is reduced there fall in the value of v (m being constant). In the last v becomes equal to zero. The molecule is at rest, is there can be no further reduction of velocity there e no lower temperature.

Questions

A

1. The following temperatures are given in degrees Centigr
0°, 15°, −273°, 100°. What are the corresponding absolute
peratures?

2. The following temperatures are given in degrees absol
0°, 100°, 273°. What are the corresponding centigrade
peratures?

3. A certain mass of gas, at 20° C., has a volume of 58
What would be its volume at (i) 0° C., (ii) 100° C.?

B

1. State Charles' law and describe an experiment to veri
A thin glass bulb is sealed at 17° C., the air pressure i
being atmospheric. The maximum internal pressure tha
bulb will withstand is 1·5 atmospheres. At what temper
will the bulb burst, the expansion of the glass being negle
Lo

2. If the density of nitrogen at 27° C. under a pressure of 7
of mercury is 1·138 gm. per litre, what is its density at 10
the pressure remaining the same? *Dur.**

3. The gas required to fill a barrage balloon to a press
75 cm. of mercury at 12° C. is stored in 10 cylinders ea
volume 0·25 cu. metre. The gas in the cylinders is at a
perature of 15·8° C. and at a pressure of 84 standard atmosp
(one standard atmosphere = 76 cm. of mercury). Fin
capacity of the balloon in cu. metres. *C.W.B.**

4. Describe how you would investigate the way in whic
volume of a fixed mass of gas heated at constant pressure ch
with the temperature.

The following results were obtained in a certain experime

Temp. (° C.) .	10	40	60	85	9
Volume (c.c.) .	26·0	29·0	31·0	33·5	3

Plot a graph of volume against temperature, arrangin
axes so that temperatures between − 300° C. and + 100° C
plotted along the X-axis, and volumes between 0 c.c. and 3
along the Y-axis. Produce the graph as far as you can be
the plotted points. Comment briefly on the graph obtained.

5. On a day when the temperature is 10° C. a cycle ty
pumped to a pressure of 80 cm. of mercury. What will b
pressure if the temperature rises to 35° C., the volume
assumed to remain constant? *Lond.**

. Describe a constant-volume air thermometer, and explain 7 you would use it to find how the pressure of a mass of gas ntained at constant volume varies with the temperature. high-altitude aircraft carries a supply of oxygen in cylinders a pressure of 180 lb. per sq. in. measured at 27° C. What be the pressure in the cylinders when the temperature inside aircraft falls to − 3° C.? *J.M.B.*

. The pressure, expressed in cm. of mercury, of the gas in a stant volume air thermometer is 74 cm., 101·1 cm., and 94 cm. n the bulb of the thermometer is immersed in melting ice, m and melting wax respectively. Find the temperature he melting wax. *O.C.**

. A sealed glass flask of air at atmospheric pressure and 20° C. nmersed in liquid air at − 180° C. Neglecting any volume nge in the flask, calculate the final pressure (in atmospheres) he flask. *Lond.**

. A mass of hydrogen occupies 200 c.c. at 17° C. and 780 mm. nercury pressure. What is its pressure when the volume is c.c. and the temperature 27° C.? *Lond.**

). A certain volume of oxygen occupies 570 c.c. at 12° C. 57 cm. pressure. What would be its volume at N.T.P.?

1. 1 gm. of oxygen at N.T.P. has a volume of 700 c.c. What ld be its volume at a temperature of 39° C. and a pressure 0 cm.?

2. An enclosed quantity of air occupies 240 c.c. at 14° C. 82 cm. pressure. What would be its volume at 28° C. and m. pressure?

3. The volume V of a certain mass of air was found to vary the temperature t as follows:

° C. . .	20·0	40·0	60·0	80·0	100·0
c.c. . .	97·7	104·6	111·0	117·1	124·3

raw a graph of V against t, and deduce *from it* the volume of gas at 0° C. *Camb.**

4. A vertical capillary tube, closed at its lower end, contains ir column of length 20·0 cm. with a mercury thread above it. en this tube is placed in melting ice, the air column contracts length of 18·9 cm.; when placed in steam, it expands to cm. Find the laboratory temperature. *Camb.**

5. A constant-volume air thermometer is arranged so that the sure in the bulb is equal to atmospheric pressure when it is ed in melting ice. When the bulb is transferred to a vessel l with steam at 100° C. the pressure is increased by 278 mm. of cury. What is the temperature of a water bath which es the pressure in the thermometer to be 100 mm. above ospheric? *Camb.**

M

CHAPTER 17

SPECIFIC HEAT, THERMAL CAPACITY, ETC.

We are all more or less familiar with milk bills, coal bil and bills including 'labour.' Milk is charged at so much p pint, coal at so much per cwt. (or ton), and labour at so mu per hour. All this is easy enough to understand. In a g bill, however, we really pay for *heat*, measured in a un known as a *therm*. It is not quite so easy to think of a ther as it is to think of a pint, or a ton, or an hour. However, is equal to 100,000 *British Thermal Units*, and a ***Briti Thermal Unit (B.Th.U.)*** is *the amount of heat required raise the temperature of* 1 *lb. of water* 1 *degree Fahrenheit.*

For scientific purposes the unit most often employed the ***calorie***, which is *the amount of heat required to raise temperature of* 1 *gm. of water* 1 *degree Centigrade.*

One further point we must mention, because we shall ne it almost at once. Just as to raise the temperature of 1 g of water 1° Centigrade it is necessary that 1 cal. should *taken in*, so when 1 gm. of water cools down 1° Centigra 1 cal. is *given out*. Indeed, we could have defined a calo as the amount of heat given out when the temperature 1 gm. of water falls 1° Centigrade.

It will be noticed that in these definitions the substa *water* is always specified, and perhaps we have asked oursel whether this really matters. Would lead or sand or mercu for instance, in the process of cooling down, give out the sa amount of heat as an equal weight of water?

It is quite easy to put this question to the test of experim

Fit a large dry test-tube (6 in. × 1 in.) with a two-holed c Through one hole push a thermometer to within an inch or s the bottom of the tube, and through the other a bent piec glass tubing (Fig. 17/1), the longer arm being 6 or 8 in. W out 30 gm. of dry sand and put it in the test-tube.

Now put the test-tube in a beaker of water and boil the lat The tube serves to prevent moisture from getting into the t tube. Meanwhile, into a second beaker put 50 c.c. of w from a measuring jar.

When the temperature of the sand has reached, say, 95° remove the cork with its fittings, and then quickly take the t

e from the water and empty the contents into the beaker of l water. Stir, and notice the highest temperature reached.

Repeat the experiment, but this time use 30 gm. of water at instead of 30 gm. of sand. In this case the 30 gm. of water be heated to 95° C. directly over a bunsen, ead of as in Fig. 17/1. Is the rise of tempera- produced by adding 30 gm. of water at 95° C., same as that produced by adding 30 gm. of d at 95° C.?

Repeat with 30 gm. of lead shot, and then with gm. of mercury. In these cases it will be bet- to use the method of heating indicated in the re.

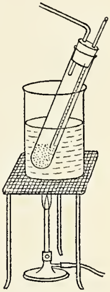


FIG. 17/1

n one such experiment it was found that adding the sand the temperature of the cold er was raised from 15° to 22°, while on add- the (hot) water it was raised from 15° to 43°. arly the water has had a much greater ting effect than the sand, in spite of the fact t it has cooled down only 52° (from 95° to , while the sand has cooled down 73° (from 95° to 22°). Water, then, in cooling down through a certain range of perature gives out much more heat than does an equal ght of sand. Correspondingly, if we wish to raise the peratures of equal weights of water and sand by equal ounts, we must supply far more heat to the water than to sand. Our experiments with mercury and lead shot ld show that the amounts of heat required for these stances are much less than those required either for water and.

t will now be clear that the amount of heat required to e the temperature of a body depends not only on the ease of temperature required and on the mass of the body, on the *material* of which the body is made. If the increase emperature required is 1° C. the amount of heat is known ne 'thermal capacity' of the body, i.e. the ***thermal capacity* *body*** is *the number of calories required to raise the tem- ture of that body* 1 *degree centigrade.*

follows from this, and from our definition of a calorie 164), that the thermal capacity of, say, 30 gm. of water ld be 30 cals., of 100 gm. of water would be 100 cals., so on.

Our experiment showed that sand has a much lower therm capacity than water. The ratio of the two is known as t 'specific heat of sand,' and similarly for other substances, i the ***specific heat of a substance*** is *the ratio of the therm capacity of that substance, to the thermal capacity of an equ mass of water.*

Suppose the thermal capacity of 100 gm. of sand is 19 ca Now the thermal capacity of an equal mass of water (100 gn is 100 cals.

$$\therefore \quad \text{specific heat of sand} = \frac{\text{thermal cap. of sand}}{\text{thermal cap. of equal mass of wat}}$$
$$= \frac{19 \text{ cals.}}{100 \text{ cals.}}$$
$$= 0{\cdot}19.$$

The thermal capacity of 1 gm. of sand is 0·19 calori Hence the specific heat of sand or other substance is *numerica* equal to the thermal capacity of 1 gm. of sand, etc. V emphasise 'numerically,' because specific heat is simply number, a ratio; while thermal capacity is expressed calories.

Suppose we are dealing with m gm. of a substance of speci heat s, and we raise its temperature by t degrees Centigra Then

s cals. will raise temperature of 1 gm. of substance by 1° C
$\therefore ms$,, ,, ,, m ,, ,, 1° C
$\therefore mst$,, ,, ,, m ,, ,, t° C

If we call this number of calories h, we have $h = mst$, very useful relationship.

Example 1. *How much heat would be required to raise the te perature of 90 gm. of mercury from 20° C. to 220° C. if the speci heat of mercury is 1/30?*

Here $m = 90$ gm., $s = 1/30$, and $t = 220 - 20 = 200°$ C.

$$\therefore \quad h = mst$$
$$= 90 \times 1/30 \times 200$$
$$= \mathbf{600\ cals.}$$

When dealing with measurement of heat, we often have consider the term 'water equivalent.' The ***water equivale of a body*** is *the number of grams of water which has a therm capacity equal to that of the body.*

Thus if the thermal capacity of a copper calorimeter is cals., its water equivalent must be 8·2 gm., because this he number of grams of water which has a thermal capacity 3·2 cals. Notice that thermal capacity and water equivalent *numerically* the same, but the first is expressed in calories, le the second is expressed in grams.

Example 2. The specific heat of aluminium is 0·217. *Find* (a) *thermal capacity,* (b) *the water equivalent, of an aluminium el weighing* 100 *gm.*

Ve could use the '*mst*' formula, but the question is easily ked out from first principles. Thus

To raise temp. of 1 gm. by 1° C. we need 0·217 cal.

,, ,, ,, 100 gm. ,, ,, ,, $0{\cdot}217 \times 100 = 21{\cdot}7$ cals.

e. thermal capacity of vessel = **21·7 *calories*.**

he water equivalent is numerically equal to this and is efore **21·7 gm.**

Vater equivalent of a calorimeter. It is often necessary to w the water equivalent of a calorimeter. This may be nd as follows:—

possible, place the calorimeter A inside a larger vessel B, ing the space between (shaded in Fig. 17/2) with felt. This ects A from heat losses.

our enough water from a measuring jar to fill A about one-d full, taking the reading before and after. difference of course gives the number of c.c. no. of gm.) in the calorimeter. Take the temture, estimating to $\frac{1}{10}$° C.

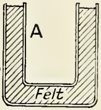


Fig. 17/2

eat some water in a beaker to about 40° C. e the temperature, and then as smartly as ible pour enough of the warm water into the rimeter to fill it about two-thirds full. Stir the thermometer and take the final tempere. By means of the measuring cylinder [1] find the total unt of water in the calorimeter. The results and calculations appear somewhat as follows:—

Wt. of cold water = 42 gm.
(measuring jar readings were 100 and 58)

Temp. of cold water . .	15·2° C.
,, ,, warm water . .	41·7° C.
,, ,, mixture . . .	28·8° C.

[1] Or the balance (in which case the weight of the calorimeter must be found). It is quite sufficient to weigh to the nearest decigram.

Total volume after adding warm water = 93 c.c.

$\therefore$ volume of water added = 93 − 42 = 51 c.c. (= 51 gm.)

Let W = required water equivalent.

51 gm. of warm water have cooled down from 41·7° to 28·8°.

$\therefore$ heat given out = 51(41·7 − 28·8) = 51 × 12·9 cals. (a)

42 gm. of water have been heated from 15·2° to 28·8°.

$\therefore$ heat taken in = 42(28·8 − 15·2) = 42 × 13·6 cals. (b)

As regards thermal capacity, the calorimeter is equivalent W gm. of water, and it has been heated from 15·2° to 28·8°.

$$\therefore \text{ heat taken in by calorimeter} = W(28{\cdot}8 - 15{\cdot}2)$$
$$= W \times 13{\cdot}6 \text{ cals.} \qquad \text{(c)}$$

$\therefore$ *total heat taken in* = (b) + (c) = (42 × 13·6) + 13·6W.

$$\therefore (42 \times 13{\cdot}6) + 13{\cdot}6W = 51 \times 12{\cdot}9$$
$$\therefore 571{\cdot}2 + 13{\cdot}6W = 657{\cdot}9$$
$$\therefore 13{\cdot}6W = 86{\cdot}7$$
$$\therefore W = \mathbf{6{\cdot}4 \text{ grams.}}$$

The thermal capacity of the calorimeter would of cou be **6·4 calories**.

Specific heat. We are now in a position to find the spec heat of a substance. We will first consider a rough meth then a more exact one.

Rough Method. Arrange a calorimeter with outer case padding, as already described, and pour into it a measu quantity of water—enough to half-fill it (but see footnote, p. 1

Tie a piece of cotton round the head of a 50-gm. weight suspend the latter for two or three minutes in boiling water.

Take the temperature of the water in the calorimeter. Br the latter near the beaker, and as quickly as possible tran the weight to the water in the calorimeter. Stir to obtain final temperature—the highest reached. The result can t be worked out.

Weight of water = 53 gm. . .	(= 53 c.c.)
Initial temperature of water . .	15·2° C.
,, ,, ,, brass . .	100° C. (assumed
Final ,, ,, mixture . .	21·2° C.
Weight of brass	50 gm.

Let s = required specific heat.

Then *heat given out* by 50 gm. of brass, of specific heat s, coo from 100° to 21·2° = 50 × s × (100 − 21·2) cals. . . . (

Heat taken in. As regards thermal capacity, the calorim itself is equivalent to 6·4 grams of water (above; we are suppo it is the same calorimeter). We may consider then that total amount of water in question is 53 + 6·4 = 59·4 gm.

'he temperature of this rises from 15·2° to 21·2°.

'. heat taken in = 59·4(21·2 − 15·2) cals. . . . . . (b)

:quating (a) and (b) we have

$$50 \times s \times 78{\cdot}8 = 59{\cdot}4 \times 6{\cdot}0$$

$$\therefore \quad s = \frac{59{\cdot}4 \times 6{\cdot}0}{50 \times 78{\cdot}8}$$

$$= \mathbf{0{\cdot}090.}$$

'he chief sources of error in the experiment are (i) loss of t in transferring the brass weight, causing the temperature he water in the calorimeter to rise *less* than it should; (ii) ttle hot water is carried with the brass weight, causing temperature of the water in the calorimeter 'ise *more* than it should. These errors often ghly cancel each other, and we get better ılts than we deserve.

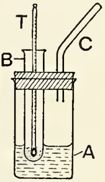


FIG. 17/3

'y using the apparatus shown in Fig. 17/3 completely eliminate error (ii), and greatly ıce (i).

. is a metal cylinder about 8 in. × $2\frac{1}{2}$ in.[1] s fitted with a good cork bored to receive wide test-tube B and the bent tube C. metal whose specific heat is required is 'ed in B preferably in the form of borings, clippings, , and is heated by boiling the water in A. Its temperature ken by the thermometer T.

/hen T is recording a steady temperature (98° or so) it 'moved, cooled under the tap, wiped and used to take the perature of the water in the calorimeter. (Cf. 'initial perature of water 15·2° C.' in previous experiment.) To the metal to the water, A is now grasped with a duster *taking care that* C *is pointing upwards* it is quickly tipped

he working out of the result is exactly as before.

he method of finding the specific heat of a substance by ing it, mixing it with water and observing the final perature, is known as the *method of mixtures*.

ıecific heat of a liquid. Sometimes this can be found by method just described. In many cases, however, heat

[1] f made of sheet zinc these cylinders last for a long time. A metal er will make enough for a class at a very modest cost.

is produced by the mere mixing of the liquid with water *the same temperature*. Alcohol mixed with water is a ca in point. In such cases we evidently cannot find the speci heat of a liquid by the method described above. Again, t method would not give good results with liquids such paraffin, which would not give up their heat readily to t water because they would tend to float on the top of it.

The best plan in such cases is to put the liquid in the calo meter and to add to it a metal of known specific heat. the operations are as already described, except that (unl the density is known) we should have to find the quant of liquid by weighing, not by measuring. Consider t following example, in which we are finding the specific h of alcohol. The metal added to it is copper, of known spec heat (0·095).

Wt. of calorimeter	64·2 gm.
Calorimeter + alcohol . . .	100·8 ,,
Wt. of copper added . . .	32·3 ,,
Initial temp. of alcohol . . .	15·5° C.
,, ,, ,, copper . . .	98·1° C.
Final ,, ,, mixture . . .	24·1° C.

W.E. of calorimeter (previously found) 6·4 gm.
Let s = required specific heat of alcohol.
Wt. of alcohol $= 100{\cdot}8 - 64{\cdot}2 = 36{\cdot}6$ gm.

Heat given out by 32·3 gm. of copper, specific heat 0· cooling from 98·6° to 24·1° $= 0{\cdot}095 \times 32{\cdot}3 \times (98{\cdot}6 - 24{\cdot}1)$
$= 0{\cdot}095 \times 32{\cdot}3 \times 74{\cdot}5$ calories.

Heat taken in (i) by 36·6 gm. of alcohol, sp. ht. s, when hea from 15·5° to 24·1° $= 36{\cdot}6 \times s \times 8{\cdot}6$ cal.

(ii) by calorimeter of W.E. 6·4 gm. when hea from 15·5° to 24·1° $= 6{\cdot}4 \times 8{\cdot}6$ cal.

Total heat taken in $= (36{\cdot}6 \times s \times 8{\cdot}6) + (6{\cdot}4 \times 8{\cdot}6)$

Now *heat given out* = *heat taken in*.

$$\therefore \quad 0{\cdot}095 \times 32{\cdot}3 \times 74{\cdot}5 = (36{\cdot}6 \times s \times 8{\cdot}6) + (6{\cdot}4 \times 8{\cdot}6)$$

$$\therefore \quad 228{\cdot}6 = 314{\cdot}8s + 55$$

$$\therefore \quad s = \frac{228{\cdot}6 - 55{\cdot}0}{314{\cdot}8} = \mathbf{0{\cdot}55}.$$

Calorific Value of Fuel. By this time we have become used to the idea that heat can be measured. Let us consider one or two heat measurements which, though

nnot conveniently be made in an elementary laboratory, e so important that we ought to know something about em.

Most people who have used both wood and coal as fuel uld agree that wood gives out less heat than an equal ight of coal, and this leads us to the question of what is led the *calorific value* of fuel, by which we mean the heat en out when one gram of the fuel in question is completely rnt. Suppose a certain kind of coal is being examined in s way. About a gram of a sample is finely powdered and ssed into the form of a cylindrical pellet. The latter is n accurately weighed and placed in a special 'bomb orimeter' designed to stand high pressure. Oxygen at atmospheres pressure is passed into the bomb, which tains a thin wire capable of being electrically heated.

The bomb is immersed in a vessel containing a known ght of water. On passing the current for a moment the l takes fire and is allowed to burn itself out, the heat lved passing into the surrounding water. Suppose this 000 gm., and that the temperature rises from 12° to 18° C. ppose also that the weight of coal is 1 gm. and that the er equivalent of the calorimeter is 100 gm. Then (omitting tain minor corrections) 1 gm. of coal when completely nt gives $1000(18 - 12)$ cals. to the water, and $100(18 - 12)$. to the calorimeter, a total of $6000 + 600 = 6600$ cals. s would be the calorific value of the fuel in question.

The calorific value of all sorts of *food* has been found in same way. 'But surely we don't use food as fuel?' you . Well, in a sense we do. In our bodies it undergoes a d of slow burning, and except for two important qualifica- s, it produces the same amount of heat as if it were burnt bomb calorimeter. The two qualifications are these.

) The body is not able to burn up the *whole* of the food, ugh in many cases (starch, sugar, fats) the percentage nt may be as much as 95 or more.

i) Very often the heat produced does not appear as such, as mechanical energy. When we walk, run, jump, etc., are using energy which is the *equivalent* of heat, and this rgy is derived from food. You will understand this better r studying the Mechanical Equivalent of Heat. in

Chapter 21. A man doing heavy physical work needs much food per day as will produce from 3400 to 4000 'gre calories' (1 great cal. = 1000 cals.). If he is doing only lig work about three-fourths of this amount is sufficient. T all-round average for the entire population should be abo 3000.[1]

Determination of high temperatures. When we are findi the specific heat of a solid such as copper by mixing h copper with cold water, we know the temperature to whi the metal was raised, and can calculate the specific he Conversely, if we know the specific heat, we can calcula the temperature.

This principle was used to some extent at one time, f finding the temperature of furnaces, etc., the metal us being platinum. The great weakness of the method is th the temperature of the mass of platinum falls very rapi when once it is removed from the furnace, and hence the val of t obtained is much too low. High temperatures are n recorded quickly and accurately by means of electric r sistance pyrometers, the action of which depends on the f that the resistance of a metal wire varies with the temperatu

Questions

A

1. How many British thermal units would be required raise the temperature of a gallon of water (= 10 lb.) from 62° to the boiling point?

2. How many calories would be needed to raise the temperat of (i) 20 gm. of water from 10° C. to 60° C., (ii) 1 kgm. of wa from 20° C. to 30° C.?

3. What is the thermal capacity of (i) a penny, assuming it weigh 9 gm. and to be made of material whose specific heat 0·095, (ii) a silver tea-pot weighing 400 gm. (sp. heat of sil = 0·057).

4. What would be the water equivalent of the teapot of q. 3

[1] These appear to be the latest 'official' figures and were put forw in 1934 by an expert committee of the British Medical Association conjunction with representatives of the Advisory Committee Nutrition of the Ministry of Health. The all-round average in N 1947 was about 2700.

B

. Define *specific heat.*

0 gm. of water at 36·3° C. are poured into a calorimeter con-
ing 50 gm. of water at 15·0° C. The final temperature
ined is 24·0° C. Calculate the water equivalent of the
rimeter.

he calorimeter is dried and 100 gm. of a different liquid are
into it. The temperature is then 15·3° C. A piece of metal
ghing 50 gm. which has been heated to 100° C. and whose
cific heat is 0·2, is placed in the liquid and the temperature
s to 26·8° C. What is the specific heat of the liquid? *Camb.*

. A mass of turpentine at 60° C. and an equal mass of water
20° C. are mixed and well stirred. Calculate the final tem-
ature, being given that the specific heat of turpentine is
cal. per gm. per deg. C. Neglect any loss of heat during
ing. *Lond.**

. Define the terms calorie, specific heat, water-equivalent.
cribe how you would determine the water-equivalent of a
rimeter by experiment.

calorimeter whose water-equivalent is 8 gm., contains 80 gm.
il at 12° C. When 100 gm. of a metal (of specific heat 0·09)
temperature of 98° C. is placed in the oil, the resulting tem-
ture is 23° C. Calculate the specific heat of the oil. *Camb.*

. A calorimeter weighing 200 gm. contains 50 gm. of water
0° C. 100 gm. of water at 80° C. is poured into the calori-
er and the final temperature on mixing is 50° C. What is
specific heat of the calorimeter material? *Dur.**

In a test on a high explosive, 0·100 gm. of the explosive
burnt slowly in a thick iron vessel, of mass 2700 gm. and
ific heat 0·111, which was immersed in 400 gm. of water.
he rise in temperature of the iron and water, allowing for
losses, was 0·101° C., find the number of calories which
d be produced by 1 gm. of the explosive. *Camb.**

A metal forging of mass 3 lb. is heated to a temperature of
)° F., and is then quenched by plunging it into oil at 60° F.
ained in a vessel whose water equivalent is 2 lb. What is
minimum mass of oil that should be used so that its tem-
ture shall not rise above 80° F.?
pecific heat of metal = 0·1. Specific heat of oil = 0·5.)
*Dur.**

Describe *one* method of measuring each of the following,
in each case explain the principle of the instrument or method
: (*a*) temperature, (*b*) quantity of heat.

qual volumes of copper and gold of specific gravities 8·9 and
respectively have their temperatures raised through 10° C.
quantities of heat absorbed by the copper and gold are in
ratio 4/3. Compare the specific heats of copper and gold.
O.C.

CHAPTER 18

LATENT HEAT

Everybody seems to know that when a kettle of wat has reached the boiling point it is useless to leave it a longer on the fire, or gas-ring, in the hope that it will beco hotter still. It would simply remain at the same temperatu (actually 100° C.) until it was all converted into stea Many people, however, who have quite clear ideas of wh happens when heat passes into boiling water, are much l certain of the effect of passing heat into *ice*. Actually, if is below 0° C. to begin with, its temperature will rise until melting point (0° C.) is reached, and will then remain consta until the ice has been completely converted into water.

The same holds good with regard to any other substa when at its melting point or boiling point, as the case may

In the present chapter we shall particularly study th 'constant temperature' states, especially the constant te perature maintained by ice during its conversion into wat and that maintained by boiling water while it is being c verted into steam.

To begin with, however, let us try to get some idea of wh happens during the heating of a solid.

In some of your P.T. drill you are standing in a particu position among your fellows, and although you make m bodily movements you do not leave the position. T molecules of a solid are something like that. They mov vibrate—but only to one side or other of a fixed cent position. If the solid is heated, the average energy of molecules is increased, for heat is a form of energy (a p we shall consider in greater detail in Chapter 21). N the kinetic energy of a molecule is represented by the prod $\frac{1}{2}mv^2$, where m is the mass and v the velocity (p. 45). T mass m is constant, so an increase in kinetic energy means increase in v.

In short, if we think of the molecules of a solid as be something like a group of boys 'spaced out' at P.T., then must think of them as moving more and more violently w

solid is heated—but still keeping close to centres fixed each one. The boys at P.T. keep their relative positions ply by taking care. The molecules, of course, do not—y keep them because of the attractive force of neighbouring lecules.

3ut as the temperature rises and the molecules vibrate 1 ever-increasing velocity, a point is reached when they rate so strongly as to break away from the attractions of r neighbours. There is an end to the 'spaced-out' ingement. The molecules glide in and out among their ghbours something like the individual lead shots in a nful of lead shot that is being stirred.[1] We say that the l has *melted*.

ote that while the solid is being melted, the energy we supplying in the form of heat is being used not to increase rate of vibration of the molecules, but to enable them to k away from the attractive forces holding them together. other words, the heat supplied is not causing an increase he *kinetic* energy of the molecules, but in their *potential* gy. It is because the kinetic energy is for the time being standstill that the temperature remains constant.

ippose we continue to apply heat after the process of ing is complete. Once more we begin to increase the tic energy of the molecules. They glide in and out with ter speed, and no doubt they vibrate with greater intensity he same time.

olecules near the surface will, in general, be kept within liquid by the combined pulls of the molecules in their hbourhood. The molecules, however, are travelling at different speeds, and if a fast-moving one at the surface pens to be travelling in an upward direction, it is likely break away from the liquid altogether. This breaking y of molecules from the surface is *evaporation*. As it is fastest-moving molecules which escape, the average speed ne remainder is reduced, and this is represented by the ng effect which always accompanies evaporation (*Junior ics*, pp. 166–8).

[1] The analogy is not very perfect, for while each shot would have a *translatory* motion, the molecule has both a translatory motion *vibratory* one.

During evaporation the only molecules that can break aw are those that happen to be travelling at comparatively hi speed when they are near the surface. But if the liquid heated, bubbles after a while begin to be formed inside t liquid, and evaporation now takes place not only from t free surface, but into the bubbles, from their inner surfac This new state of affairs, in which the interior of the liqu is concerned as well as the free surface, is known as *boili* and evaporation is now much more rapid because it is taki place from a greatly extended surface.

Suppose a flask of water is boiling over a bunsen burn and we then introduce an extra bunsen. What happens?

The existing bubbles are enlarged, and more bubbles formed, increasing the (internal) surface at which evaporati takes place. Thus we have an increased rate of evaporati But, as we have already seen, evaporation is accompanied loss of heat, and the increase in this rate of loss just balan the gain of heat from the extra bunsen. That is why temperature does not rise.

Latent heat of fusion. When ice is melting, the heat pass into it is said to be *latent* (= hidden), because it cannot detected by the thermometer. The ***latent heat of fus of ice*** is *the number of calories required to convert* 1 *gram of at* 0° *C. into water at the same temperature.* You can, no dou modify this definition for yourself, so as to make it ap to solid substances in general.

Instead of 'latent heat of fusion of ice,' the shorter t 'latent heat of ice' is often used. The method of find the latent heat is seen in the following experiment:—

Take a double-walled calorimeter (Fig. 17/2, p. 167), weigh the inner vessel (to one decimal place only; and so fo weighings in this experiment). Half fill the calorimeter water and weigh again.

Using a small bunsen flame, warm the calorimeter until temperature of the water is about 6 degrees above that of room, and then place it inside its padded enclosure.

Now break up some ice into pieces about the size of peas, dry them by rolling them over on a sheet of blotting-paper. suitable quantity would have, roughly, one-eighth the weigh the water in the calorimeter.

Take the temperature of this water (reading to 0·1° C.) quickly add the ice, picking up the latter by means of cruc

s (preferably with blotting-paper tied round the tips). Stir he time with the thermometer, and record the lowest temure reached. Weigh again so as to find out how much ice been added. The results are then worked out as follows:—

ppose (a)	Wt. of calorimeter	62·3 gm.
(b)	Calorimeter + water . . .	133·6 ,,
(c)	Calorimeter + water after addition of ice	142·4 ,,
	Initial temperature	21·3° C.
	Final temperature	11·2° C.
	W.E. of calorimeter (p. 168) . .	6·4 gm.

eight of ice used = (c) − (b) = 8·8 gm.

t l = required latent heat.

en heat required to melt 8·8 gm. of ice = 8·8l cals.

ote that 8·8l cals. suffices only to *melt* the ice, i.e. to turn it water at 0° C.) In our experiment this melted ice is raised emperature of 11·2° C., and this requires a further quantity at equal to (8·8 × 11·2) cals.

total amount of heat required to convert 8·8 gm. of ice at into water at 11·2° C. = 8·8l + (8·8 × 11·2) cals. . (A)

is heat has been supplied by the cooling of the water in the imeter (133·6 − 62·3 = 71·3 gm.) from 21·3° to 11·2°, and by the cooling of the calorimeter itself (= 6·4 gm. of water).

al weight of water may be taken as 71·3 + 6·4 = 77·7 gm.

l of temperature = 21·3 − 11·2 = 10·1°.

heat given out = 77·7 × 10·1 cals. . . . . . (B)

uating (A) and (B) we have

$$8{\cdot}8l + (8{\cdot}8 \times 11{\cdot}2) = 77{\cdot}7 \times 10{\cdot}1$$
$$\therefore \quad 8{\cdot}8l + 98{\cdot}6 = 784{\cdot}8$$
$$\therefore \quad 8{\cdot}8l = 686{\cdot}2$$
$$\therefore \quad l = \mathbf{78.0\ cals.\ per\ gm.}$$

e or two points connected with this experiment call for f discussion.

Weighing only to one place of decimals. We cannot read eratures more accurately than to one place of decimals, is useless to take weighings to two places. 'A chain is onger than its weakest link.'

Preliminary heating of water. Suppose this is heated °, and cools down to 11°, the temperature of the room 16°.

may divide the cooling process into two parts: (*a*) 21° to 16° and (*b*) from 16° to 11°.

During (*a*) the water is *warmer* than the air in the ro and so loses some heat to the air.

During (*b*) the water is *colder* than the air, and so g heat from the air.

If the initial temperature is just as much above that of room as the final temperature is below it (as in the case u discussion) the two errors will cancel out. To find exactly how much to warm the water, a preliminary exp ment is evidently necessary.

(iii) *Drying the ice and using padded tongs.* In our cal tions we assume that no ice is melted except by heat obta from water in the calorimeter. Evidently this is true if the ice is dry when it enters the calorimeter.

(iv) *Padding the calorimeter.* This, of course, is commo nearly all experiments in which a calorimeter is used, an intended to minimise loss of heat to the air and the suppor table (or equally, to minimise gain of heat).

Latent heat of vaporisation. We have seen that it tak great deal of heat—actually 80 cals.—simply to melt 1 gm ice without producing any rise of temperature. Simil when water is boiling it takes a great deal of heat simpl turn 1 gm. of it into steam without rise of temperature. heat is known as the ***latent heat of vaporisation of wate*** more shortly, as the ***latent heat of steam***, and may be form defined as *the number of calories required to convert one of boiling water*[1] *into steam at the same temperature.*

A method[2] now much used for finding the latent he steam involves the use of a heavy calorimeter.

The apparatus is represented in Fig. 18/1. Water is b in the tin vessel A (or a flask might be used) and passes int heavy metal calorimeter B, which is surrounded by a felt c B has previously been weighed on a 'household balance.' S can escape through the bent tube C.

To begin with, the calorimeter B is at the temperature o room, which is noted. When steam begins to enter, it conde giving up its latent heat to B, the temperature of which is ra Once B has attained a temperature of 100° C. it is unab

[1] The boiling point varies according to the pressure, and so st speaking, there is a special latent heat for each boiling point. shall confine ourselves, however, to the case of the boiling poi normal pressure, which for water would be 100° C.

[2] Devised by Mr. A. R. Marshall, H.M.I.

ndense any more steam, and the latter then begins to escape ough C. When it is escaping freely the bunsen is turned out, l the inverted calorimeter with its cork and two tubes is noved. The felt is taken off, and the calorimeter is held under tap, to cool the contained water. The latter is then measured ner in a cylinder or (better) by pouring it through a funnel o a burette. The specific heat of the metal of which the orimeter is made must be known, and the result is then worked as follows:—

Weight of calorimeter	1142 gm.
Specific heat (brass)	0·092
Temperature of room	15·4° C.
Wt. of steam condensed (16·8 c.c.) . .	16·8 gm.

et L = required latent heat.

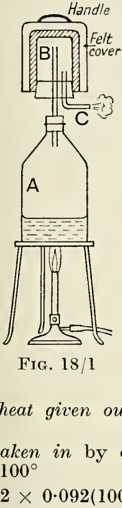


Fig. 18/1

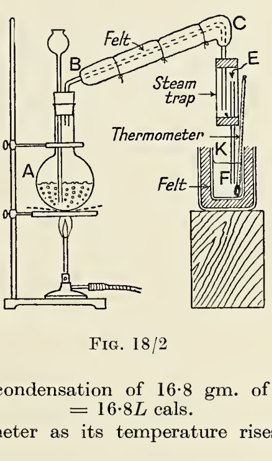


Fig. 18/2

hen *heat given out* by condensation of 16·8 gm. of steam $= 16{\cdot}8L$ cals.

eat taken in by calorimeter as its temperature rises from ° to 100°

$= 1142 \times 0{\cdot}092(100 - 15{\cdot}4) = 1142 \times 0{\cdot}092 \times 84{\cdot}6$ cals.

quating, we have $16{\cdot}8L = 1142 \times 0{\cdot}092 \times 84{\cdot}6$

giving $L =$ **529**

he method gives very fair results. The chief source of r is in connection with 'weight of steam condensed.' above typical result shows that an error of 1 gm. in this ld throw the result out by about 30 units. Some is apt

to be lost by evaporation, and by clinging to the sides of t jar or burette.

The container A should not be more than, say, a th full; otherwise, during boiling, water is apt to be thro up into the calorimeter.

Another method. An older method, in which steam is pas into cold water, is still widely used.

The apparatus of Fig. 18/2 is fitted up. Water is boiled the flask A, and the steam passes through the tube BC, whic packed round with felt. BC is given a backward slope so t condensed steam may run back into the flask. Some conden steam is also caught in the steam-trap (really a water-tr From the latter an exit tube EF passes into the calorimeter contained as usual in an outer vessel lined with felt or cotton-w

The calorimeter is first weighed empty, then about two-thi full of water (one decimal place). Before placing the calorim in position, the water in A is allowed to boil freely for two or th minutes so that all tubes, etc., may be thoroughly heated. T greatly reduces the amount of steam condensed *en route* to calorimeter.

The temperature of the cold water in the calorimeter is n taken, and steam is passed in until the temperature has ri 30° or so. The calorimeter is then withdrawn and the fi temperature taken. It is then weighed *quickly*, because warm water contained in it evaporates rather quickly. Supp

Weight of empty calorimeter	62·3 gn
Calorimeter + water	153·4 ,,
Calorimeter + water + condensed steam .	158·5 ,,
Initial temperature	15·7° C
Final temperature	45·9° C
W.E. of calorimeter	6·4 gn

Let $L =$ required latent heat. As L calories are required convert 1 gm. of water at 100° into steam, we shall assume t when 1 gm. of steam at 100° condenses to water (still at 100° gives out L cals.

In our experiment, wt. of steam condensed

$$= 158{\cdot}5 - 153{\cdot}4 = 5{\cdot}1 \text{ gm.}$$

$\therefore$ heat given out during condensation $= 5{\cdot}1L$ calories.

The condensed steam then cools from 100° to 45·9°, giving a further $5{\cdot}1(100 - 45{\cdot}9) = 5{\cdot}1 \times 54{\cdot}1$ cals.

$\therefore$ total of heat given out $= 5{\cdot}1L + (5{\cdot}1 \times 54{\cdot}1)$ cals. . (A

Wt. of water in calorimeter $= 153{\cdot}4 - 62{\cdot}3 = 91{\cdot}1$ gm., the calorimeter itself is equivalent to 6·4 gm.

$\therefore$ wt. of water may be taken as 97·5 gm.

Temperature of this water is raised from 15·7° to 45·9 = 3

$\therefore$ heat taken in by water $= 97{\cdot}5 \times 30{\cdot}2$ cals. . . . (B

Equating (A) and (B) we have

$$5{\cdot}1L + (5{\cdot}1 \times 54{\cdot}1) = 97{\cdot}5 \times 30{\cdot}2$$

Solving, we obtain $L =$ **524 calories per gram.**

The chief sources of error are: (i) evaporation after passing e steam (already mentioned); (ii) the increase in weight should due entirely to *steam* entering the calorimeter. Actually me water enters (due to premature condensation). This error reduced by making the tube EF as short as possible.

We will conclude this chapter with two numerical examples.

Example 1. *An aluminium kettle weighs* 100 *gm. and* 1 *litre of ter is put into it. Its temperature is* 15° *C. It is then placed a gas ring and in* 10 *minutes the water boils. If heat continues be supplied at the same rate, how long will it be before all the water ls away? (Specific heat of aluminium* = 0·22 *and latent heat steam* = 540.)

(i) Heat required to raise temperature of 100 gm. of aluminium from 15° C. to 100° C. $= 0{\cdot}22 \times 100 \times (100 - 15)$

$= 0{\cdot}22 \times 100 \times 85$ cals. $= 1870$ cals.

Heat required to raise temperature of 1 litre (= 1000 gm.) of water from 15° C. to 100° C.

$= 1000 \times 85$

$= 85{,}000$ cals.

Total amount = 85,000 + 1870 = 86,870 calories.

ii) Heat required to evaporate 1 gm. of water = 540 cals.

$\therefore$ heat required to evaporate 1000 gm. = 540,000 cals.

From (i) we see that the gas-ring supplies 86,870 cals. in 10 nutes = 8687 cals. per minute.

In (ii), 540,000 cals. are required.

$$\therefore \text{ time required} = \frac{540{,}000}{8687} = \mathbf{62{\cdot}2 \text{ minutes.}}$$

Example 2. 12 *gm. of steam are blown into a large block of How much ice would be melted? (Latent heat of steam* = 540; *nt heat of ice* = 80.)

In the process of condensing, 12 gm. of steam will give out $\times$ 540 = 6480 cals.

In the further process of cooling down from 100° to 0°, heat en out by water $= 12 \times 100 = 1200$ cals.

Total amount of heat given out = 6480 + 1200 = 7680 cals.

Now for every 80 calories given out, 1 gm. of ice is melted.

$$\therefore \text{ no. of gm. of ice melted} = \frac{7680}{80} = \mathbf{96.}$$

Questions

A

1. How many calories would be needed (i) to raise the te perature of 10 gm. of ice from $- 20°$ C. to the melting poi (ii) to melt the ice; (iii) to raise the temperature of the ice-o water to 100° C.; (iv) to evaporate the water? (Specific heat ice = 0·5; the latent heat of fusion of ice = 80 cals. per gr latent heat of vaporisation of water = 540 cals. per gm.)

2. 100 gm. of steam at 100° C. are blown into the middle a quantity of ice at 0°. How much ice would be melted? (Late heats of fusion and vaporisation as given in q. 1.)

3. 10 gm. of ice at 0° C. are dropped into 50 gm. of water 20° C. Find the final temperature. (Latent heat as in q. 1.)

4. 10 gm. of steam at 100° C. are passed into 100 gm. of water 20° C. Find the final temperature. (Latent heat as in q. 1.)

B

1. Describe simple experiments, one for each case, to illustr the meaning of the terms *latent heat, specific heat.*

15 gm. of dry ice at 0° C. are dropped in 200 gm. of liquid specific heat 0·52 cal. per gm. per deg. C., contained in a calo meter of water equivalent 15 gm. If the original temperat of the liquid was 30° C., find the temperature when the ice has ju melted. (The latent heat of fusion of ice is 80 cal. per gm.) *Lo*

2. Define *latent heat of fusion* of a solid. Describe how y would measure the latent heat of fusion of ice.

What mass of ice at 0° C. must be mixed with 500 gm. of wa at 17° C. to lower its temperature to 10° C.? The water equival of the vessel containing the water is 13 gm. (The latent heat fusion of ice is 80 cal. per gm.) *Lond.*

3. A thermos flask whose water equivalent is 30 gm. conta 500 gm. of water at 20° C. What is the least amount of required to cool the water and flask to 0° C.? *Dur.*

4. Describe an experiment to show that water expands solidification. Give *two* examples of other substances which a expand on solidification.

During a storm, a depth of 4 cm. of rain falls on the surf of a frozen pond. The temperature of the rain is 8° C. and t of the ice 0° C. Find the thickness of ice melted, given that S.G. of ice = 0·92, and the latent heat of fusion of ice = calories per gram. *O.C.*

5. 50 gm. of mercury are frozen in a block of solid car dioxide to $- 80·0°$ C. and transferred to a calorimeter (of wa equivalent 4 gm.) containing 36 gm. of water. The temperat falls from 17·5° C. to 10·0° C. Taking the specific heat of merc in both the solid and liquid states to be 0·033, calculate its lat heat of fusion. *Camb.**

. A calorimeter of water equivalent 10 gm. contains 100 gm. vater and 10 gm. of ice. How much steam must be passed) the calorimeter to raise the temperature to 50° C.? (Latent t of ice = 80 calories per gm.; latent heat of steam = 540 ries per gm.) *Dur.**

. Suggest an experiment to show that water can be frozen its own evaporation. What weight of water at 0° C. must porate in order to freeze 1 gm. of the remaining water? tent heat of fusion of ice at 0° C. = 80 cal. per gm.; latent t of evaporation of water at 0° C. = 606 cal. per gm.) *Camb.**

. What do you understand by the terms: the *thermal capacity* body, the *latent heat of vaporisation* of a substance, *melting nt*?

copper calorimeter of water equivalent 10 gm. contains gm. of water and 100 gm. of ice, all at 0° C. Heat is supplied t electrically at the rate of 500 cals. per sec. How many nds from the start will it take for (*a*) all the ice to melt, (*b*) calorimeter and contents to be at 100° C., (*c*) the calorimeter ave boiled dry? (Latent heats of water and steam = 80 and cals. per gm. respectively.) *Camb.*

Explain why a cooling effect accompanies the evaporation iquids and give *two* examples. Describe an experiment in ch water is frozen by evaporation.

alculate how much steam at 100° C. will melt 10 gm. of ice ° C. if the water produced remains at 0° C. Take the latent s of fusion and evaporation of water as 80 cal./gm. and 540 gm. respectively. *O.C.*

). Give an account of the mode of action of a steam engine, illustrate your answer with a large clear diagram.

steam is generated by means of a gas heater, find the cost hanging 1 gallon of water at 40° F. into steam at 212° F., g given that 55 per cent. of the heat supplied by the com- ion of gas is utilised in heating the water and changing it steam, and that the cost of the gas is fourteen pence per m. (1 gallon of water weighs 10 lb. 1 therm = 10^5 British rmal Units. Latent heat of vaporisation of water = 972 ish Thermal units per lb.) *C.W.B.*

CHAPTER 19

VAPOUR PRESSURE

We all know that when water evaporates it disapp completely—water vapour is just as invisible as air its The air round about us always contains more or less of t invisible vapour. We know, too, that important resu follow from its presence—that somehow it is connected w such subjects as mist, fog, dew and other weather phenome Let us try to turn our rather hazy knowledge of water vap and the part it plays into something fuller and more exact

Saturated and Unsaturated Vapour. We can learn a great deal from a few simple experiments with a barometer tube. A tube AB about a yard long is completely filled with mercury and inverted in a dish of mercury. The column of liquid falls a little, leaving a vacuum in the space AC, while the length DC is 'the height of the barometer.' It is a good plan to mark the position of C with gummed paper.

Some water is now boiled well to free it from air, and after cooling, a very tiny quantity is passed upwards through the mercury into the space AC. This is best done by means of a fountain-pen filler, the end of which has been bent in a gas-flame.

If the quantity of water introduced has been sufficiently small it will vaporise completely on entering the vacuum, and the mercury will be pushed down a millimetre or two to the level G (Fig. 19 in which, however, the mercury must be supposed to r upwards as far as G. The length CG (say 1·5 mm. of m cury) is a measure of the vapour pressure.

Fig. 19

On introducing a further tiny quantity of water the mer is pushed down a little more, but a stage is very soon rea at which the space is 'saturated' with vapour. More w may be introduced, but it simply rests unvaporised on

) of the mercury (EF in Fig. 19/2), while the mercury level 10 longer depressed. We are supposing that we have been rking at 'room temperature,' say 15° C. throughout. In t case, CE would measure 12·7 mm.,[1] and we say that e maximum pressure of aqueous vapour at 15° C. is 12·7 1.'—'Maximum,' because at 15° C. water vapour can exert / pressure between zero and 12·7, according to the amount sent. When the space is saturated, the depres- 1 reaches its maximum value, 12·7 mm.

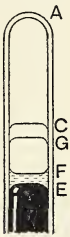


Fig. 19/2

f we compress a given quantity of *air* into a iller space, we increase its pressure (Boyle's v). If, however, we compress our *saturated vapour*) a smaller space,[2] all that happens is that some t condenses and the pressure remains constant at 7 mm. If we increase the volume of the space , enough of the surplus water vaporises to keep space saturated and to keep the pressure at 7 mm., until, of course, the space becomes so e that all the surplus water is vaporised; beyond point the space becomes unsaturated, and the pressure ns to fall.

ontrast all this with the case of an unsaturated vapour confined space. As we increase the space, the vapour sure becomes less. As we decrease it, the pressure eases up to the point at which the space is saturated.

o other liquids, at 15° C., exert a maximum vapour sure of 12·7 mm.? The question is easily answered by ating the whole experiment, but using alcohol instead of er. A maximum pressure of 33·0 mm. is obtained. With r it is 354 mm. Sulphuric acid, on the other hand, gives apour pressure of less than 1/100 mm. Evidently this imum pressure, at a given temperature, varies a great deal 1 one liquid to another.

) far all our experiments have been carried out at 15° C., hatever 'room temperature' happened to be. Now, going to the barometer tube with a little unvaporised water the mercury (Fig. 19/2), let us warm the space AE a

[1] It is not suggested, however, that such an accurate result could be ned with the simple apparatus described.

[2] Easily done by pushing the barometer tube farther down into the of mercury.

little by waving a bunsen flame over it. Some of the wa vaporises, and the mercury is at once pushed farther dov Evidently *the maximum pressure of aqueous vapour increa with temperature.*

Much more exact experiments can be carried out w the apparatus shown in Fig. 19/3. Here the barometer tu is graduated, and is enclosed in a wider glass tube throu which water from a geyser can be circulated. A thermome through the upper cork gives the temperature.

Suppose we wish to find the maximum pressure of aqueous vapour at 40° C. We regulate the flow of water from the geyser until the temperature is as steady as possible at 40°. We take the barometer reading, pass in some water with the curved filler and take the reading again (making sure, of course, that there is a little unvaporised water above the mercury). Suppose the readings are respectively 762 mm. and 707 mm. Evidently the required vapour pressure is 55 mm.

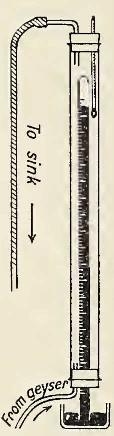


Fig. 19/3

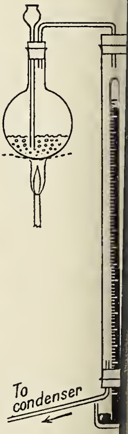


Fig. 19/4

An important special case is the pressure[1] of aqueous vapour at the boiling point. Here we must discard e geyser, and connect the upper tube to a flask genera g steam, which passes round the barometer tube and esc s through the lower tube (then, preferably, through a conden).

When the steam has been passing a little time it is fo d that the mercury in the barometer tube is pushed down A (Fig. 19/4)—i.e. to the level of the mercury in the outer n. The pressure inside the tube is therefore equal to that o e atmosphere. A similar result is obtained for other liqui -

[1] 'Maximum' is understood unless the contrary is stated.

g. the pressure of ether vapour at 35° (this being the boiling int of ether) is equal to that of the atmosphere.

N.B. In the last experiment it would be easier, and much safer, let water at 35° circulate through the wide tube, than to make e of vapour from boiling ether.

We may therefore state generally that *the maximum vapour essure of any liquid, at its boiling point, is equal to the pressure the atmosphere.*

Relative Humidity. We often talk about the air being amp.' We perspire, and the perspiration remains on our dies instead of drying off. At such times a line of washing y take many hours to dry, although no rain is falling. At ier times we talk about the air being 'dry.'

t is important to notice, however, that the sensation of npness or dryness depends not so much on the amount of isture actually present, as on what is called the ***Relative midity***, this being defined as *the ratio of the amount of er vapour present in a given volume of air, to the amount uired to saturate that volume of air at the same temperature.* instance, 1 cubic yard of air at 20° C. requires 13·0 gm. water vapour to saturate it, while if the temperature is C., only 7·1 gm. would be required. Suppose the amount water vapour actually present is 6·5 gm. Then if the nperature is 20° C., relative humidity

$$= \frac{\text{amount present}}{\text{amount required to saturate}} = \frac{6 \cdot 5}{13} = 0 \cdot 5, \text{ or } 50\%.$$

he temperature is 10° C., relative humidity $= \frac{6 \cdot 5}{7 \cdot 1} = 0 \cdot 92$ or %. The air would feel very much 'damper' in the second than in the first, because, although it contains only the e amount of water vapour, it is nearer to saturation point.

or many purposes it is important to be able to determine relative humidity of the atmosphere. It is needed, for ance, in making forecasts of the weather, in deciding ther the atmosphere of a cotton-mill is suitable for spinning weaving, and in many other cases.

method of determining relative humidity is indicated in 19/5 (only roughly, for there are various refinements considered here. Ignore the flask F for the present). a tube containing some substance which will readily

absorb water vapour—calcium chloride, for instance. It connected with a large bottle or aspirator B. A is weigh and then air is drawn slowly through it by turning on slow stream of water at C. Suppose that we have run 5 litres of water, and that the weight of A has increased 0·045 gm. Then the weight of water vapour present litre = 0·045 ÷ 5 = 0·009 gm. Suppose the temperat is 20° C. Reference to tables shows that at this temperat 1 litre of air if saturated with water vapour would h 0·017 gm.

∴ relative humidity = 0·009 ÷ 0·017 = 0·53, or 53%

Instead of referring to tables, it is instructive to rep the experiment with the addition of, say, three flasks (or bett

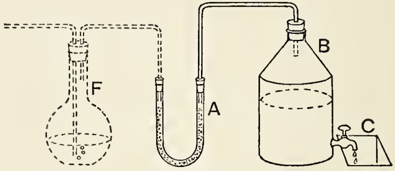


Fig. 19/5

Winchester quart bottles) containing water, of which o one, F, is shown in the diagram. The same volume of wa is run out as before. The idea is, of course, to find what wei of water vapour is required to *saturate* the given volume of but the results obtained are usually too low, making relative humidity come out too high.

The processes just described are evidently very tedi and much shorter methods are in use depending on a de mination of the ***dew-point***, which is *that temperature at wh the moisture actually present in the air would be sufficien saturate it.*

Think of a cubic yard of air at 20° C. containing 7·1 of water vapour. That is much less than the amount (1 gm.) which would be required to saturate it. Now let air be cooled down, the amount of water vapour in it remai constant at 7·1 gm. The vapour-holding capacity of air becomes less and less, until at a certain temperatu

ually 10° C.—the 7·1 gm. of vapour is sufficient to saturate At this temperature the air begins to deposit its moisture the form of dew. We shall see presently how to find the w-point (10° C. in the case just considered).

Now, from tables we can find the amount of water vapour uired to saturate 1 cubic yard of air at any given temature, and we know that

$$\textit{Relative humidity} = \frac{\textit{weight actually present per cu. yd.}}{\textit{weight required to saturate 1 cu. yd.}}$$

e numerator of this fraction is 7·1 gm., for the 'weight ually present' did not change on cooling until the dewnt was reached, and this amount was just sufficient to urate the air at the dew-point. The denominator is **13·0**.

$$\text{Hence Relative humidity} = \frac{7 \cdot 1}{13} = 0 \cdot 53 \text{ or } 53\%.$$

Notice that so long as the temperature is constant, the ght of a gas present in a given volume, say 1 cubic yard, proportional to the pressure. Hence in the fraction given ve we may read 'pressure' instead of weight, and we get ative humidity

$$= \frac{\textit{actual pressure of aqueous vapour at existing temp.}}{\textit{maximum pressure of aqueous vapour at existing temp.}}$$

$$= \frac{\textit{maximum pressure of aqueous vapour at dew-point}}{\textit{maximum pressure at existing temperature}}.$$

xample. *Find the relative humidity of air at* 15° *C. if the dew-t is found to be* 8° *C.* (*Maximum pressure of aqueous vapour* 5° *C. is* 12·67 *mm. and at* 8° *C. is* 7·89 *mm.*)

$$\text{R.H.} = \frac{\text{Maximum pressure of aqueous vapour at } 8° \text{ C.}}{\text{Maximum pressure at } 15° \text{ C.}}$$

$$= \frac{7 \cdot 89}{12 \cdot 67} = 0 \cdot 623 \text{ or } \mathbf{62 \cdot 3}\%$$

o find the dew-point. About two-thirds fill a bright aluium beaker with water. Add a bit of ice from time to time, ing with a thermometer after each addition. Avoid breath-too near the beaker. Observe the temperature at which metal surface begins to become misty, say 8° C. Now let vessel gradually warm up, and observe the temperature at h the mist begins to disappear, say 9°. The dew-point may aken as 8·5°, the mean of the two readings.

An instrument used for finding the dew-point is kno as a ***hygrometer***. The simple hygrometer just descril does not give very accurate results, though it is good for givi us a general idea of the subject. A much better instrumen Regnault's hygrometer (Fig. 19/6). This consists of a sort test-tube, the lower part of which is made of thin silver, higl polished on the outside. The tube contains ether, which rapidly evaporated by blowing air through it. The evapo tion produces cooling, and the temperature at which a m appears is recorded by a thermometer dipping into the eth

In modern forms of the instrument, the apparatus just described is enclosed in a box. The silver portion is brightly illuminated by means of an electric light, and the observations are made through a window in the side of the box. In this way local variations of humidity due to the observer's breath are prevented.

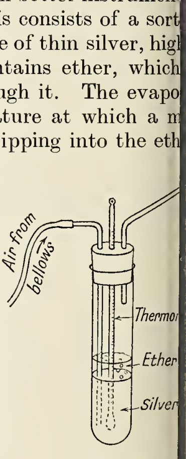


FIG. 19/6

Conditions for heavy dew. When the temperature of the atmosphere falls to dew-point, dew will begin to be deposited. The amount of this deposit will depend on circumstances.

We are more likely to have a heavy fall of dew after a *hot day*, because the air will have tal up more water in the form of vapour. Next, it is desira that the earth's surface should be able to cool as complet as possible by radiation, and for this we require a *cl sky*.

The air lying close to the earth's surface must remain that position while it is cooling down to the dew-point, so require *absence of wind*.

Again, a solid body which is a good conductor may become very cold, because the heat lost by radiation constantly replenished by heat conducted to it from earth below. Such a body is less likely to receive a dep of dew. For instance, there may be dew on a wooden fe but none on some iron railings close by.

Summing up, we may say that the best conditions fo copious deposit of dew are a calm night with a clear

wing a hot day; and the dew will be deposited on non-lucting materials more than on conducting ones.

may happen that the dew-point is below 0° C. In that the water vapour in the air will be condensed in the solid , *i.e.*, as *hoar frost*. If there is no such deposit, though temperature is below freezing point, we speak of a *black*

weating' of Walls. Recently built walls often 'sweat,' damaging results to wallpaper if this is put on too soon. water is produced as the result of a chemical action een the mortar and the carbon dioxide of the air $)H)_2 + CO_2 = CaCO_3 + H_2O)$. If the air near the wall eady saturated, the additional moisture thus formed is le to evaporate, and trickles down the wall.

e formation of 'dew' on grass is in some respects similar, art or all of the deposit may be the result of transpiration blades of grass.

st and Cloud. Very often the air for some distance above urface layer is also cooled to dew-point (or, of course, it), and particles of moisture are formed, giving a *mist g*.[1] There are always minute particles of dust in the sphere, and apparently these serve as the nuclei round the water vapour is precipitated.

uds are usually formed as the result of an upward nt of moisture-laden air. The farther this rises from arth, the lower becomes its pressure, and consequently pands (Boyle's law). This expansion produces cooling,[2] cloud is produced—a cloud being a bank of mist or fog d at some distance above the earth's surface. The tiny les of water may run together, forming drops sufficiently d heavy to fall as *rain*.

dissipate the fog it would, of course, be necessary to raise the rature of the air above dew-point. To do this *artificially* requires large amount of heat, but it is done occasionally to assist airmen ding. Petrol is used as the source of heat, and the process is because of the large quantity required.

mpression of a gas produces *heat*, as when a bicycle pump is worked. With expansion we have the opposite effect. This will be clearer after Chapter 21 has been read.

Questions

1. Describe an experiment to show the difference betwee unsaturated and a saturated vapour. *Lond.**

2. How would you show that the temperature at which w boils depends on the pressure on the water? Deal with press above and below atmospheric pressure, in each case indica how the pressure is measured and drawing a good diag *Camb*

3. Explain what is meant by a saturated vapour.

What is the effect on the pressure of a saturated vapour o decreasing the volume, (*b*) increasing the temperature?

When the upper fixed point of a thermometer is being te accurately, care is taken (i) to have the thermometer bulb in steam from boiling water, and not in the water itself, (ii) to the pressure of the atmosphere at the time of the test. Ex as fully as you can the reason for these two precautions. *O*

4. Why, in cold weather, does mist form on the eye-gl of a person entering a warm living-room? *Brist.**

5. Explain why the 'steam' from a railway engine (or a ke is invisible near the funnel (or spout). *Camb.**

6. Why does snow disappear in clear sunny weather whil temperature remains below freezing point?

7. Describe an experiment to show that a vapour exe pressure and that the vapour pressure at the boiling-poi the liquid is equal to the atmospheric pressure. *C.W.B.**

8. What are the chief differences between evaporation boiling?

Some water is introduced into the Torricellian vacuum barometer tube of fairly wide bore until a column 5·44 cm. stands above the mercury. The temperature of the labora is 20° C. and the atmospheric pressure 753 mm. of mer Find the height of the mercury column. (Specific gravit mercury = 13·6. Saturated vapour pressure of water at 20° 17·5 mm.) *J.M.B.*

9. What is meant by the term *dew point*; How would determine it by experiment?

Under what conditions will hoar frost be formed?

What must be the condition of the atmosphere when the point is high, and when it is low in comparison with th temperature? *Dur.*

10. Describe how the following can be demonstrated: vapour exerts a pressure, (*b*) this pressure is a maximum the vapour is saturated, (*c*) the maximum vapour pressu independent of the volume occupied by the vapour.

The maximum vapour pressure at 40° C. of alcohol is 133 of mercury whilst that of ether is 921 mm. State which the higher boiling point and give reasons for your answer. *J.*

CHAPTER 20

TRANSMISSION OF HEAT

Chapters 18–20 of our earlier book we saw that heat is smitted by the three processes of conduction, convection radiation. Here we shall content ourselves with a brief sion of the first two, but shall break up a considerable unt of new ground in Radiation.

e may define ***Conduction*** as *the process by which heat es from one portion to another of a body (or of two or more s in contact) with an increase in temperature at all interate points, but without any ge in the position of these ts relative to one another.*

crease in temperature at mediate points is specified s to exclude radiation (a er we shall be discussing ently), while the last clause serted so as to exclude ection.

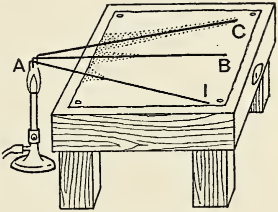


Fig. 20/1

e conductivity of various s in a room may be pared roughly by touch, the best conductors feeling st. A much more accurate method is to use heattive paper. Fig. 20/1 represents thin wires of the same nsions made of copper, brass and iron respectively, d fan-wise over such paper, and equally heated by a en placed just under A. We wait until the green band spread to its maximum extent along each wire. The of these 'green band' distances then gives the order of onductivities.

hen we try to study the conductivity of liquids, our ts are apt to be entirely upset by the fact that conon sets in. To avoid this, we may heat the liquids from op. Fig. 20/2 illustrates an experiment to show the conductivity of water. The piece of ice is wrapped round

with a little copper wire to make it sink, and it is found t the water at the top may be made to boil while the ic the bottom is still unmelted.

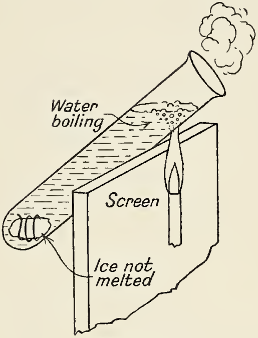


FIG. 20/2

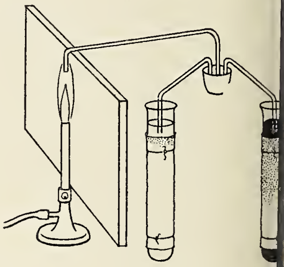


FIG. 20/3

Fig. 20/3 indicates a method of finding which of two liq (e.g. mercury and water) is the better conductor. The liquids are equally heated, from the top, by means of stout copper wires dipping into a crucible of heated merc Heat-sensitive paper is bound to each test-tube.

A good conductor consisting of stout brass gauze forms an essential feature of the Davy lamp (Fig. 20/4). If the explosive gas 'fire-damp' should be present, it can easily pass to the inside of the gauze, where it burns as a blue cap above the ordinary flame. The flame, however, does not pass through the gauze, because the latter conducts the heat away so freely that the explosive mixture on the outside never reaches its 'ignition temperature.'

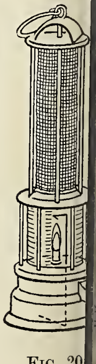


FIG. 20

Bad conductors are very widely used in everyday life. Clothing, blankets, eiderdowns, etc. are all bad conductors, intended to prevent a too rapid loss of heat from the body.

e leather or rubber sole of a shoe serves the same purpose. may be wrapped in sacking, flannel, sawdust, etc. to prevent it passing into it from the outside air.

Air is itself an exceedingly bad conductor, and so fabrics ich contain much air entangled in their substance are very viceable as material for clothing, bedding, etc. Cotton-ol forms a particularly 'warm' packing, say when it is uired to prevent the heat of a poultice from escaping too idly. A bird makes use of the bad conductivity of air en it puffs out its feathers in cold weather, and a dog can ke its hair stand out in much the same way. A camper fers two thin blankets to a single thick one, because the ner arrangement gives him an a blanket of air.

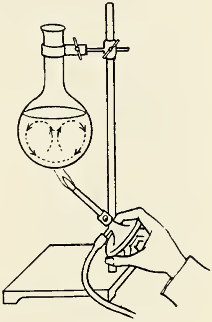


FIG. 20/5

ll gases, and nearly all liquids, very bad conductors. Heat is ally transmitted through them quickly, however, by ***convec-***, which we may define as *a ess in which heat is conveyed from part of a fluid*[1] *to another, by al movement of the heated portions e fluid.*

is easy to account for this ement. The part of the fluid is being heated expands. This es it to become less dense than unheated portions, and so it rises, place being taken by colder portions of the liquid or gas. process may be illustrated by the following experiment:—

pport a flask of water by means of a clamp (Fig. 20/5). e a glass tube in the water, reaching to the bottom, and drop nall crystal of potassium permanganate down the tube. ıdraw the latter, first putting your finger over it. Heat the by holding the tip of a *small* flame near it. The crystal a purple solution, and by means of this we can trace the ement of the water, which is somewhat as indicated by the vs.

a liquid underwent no change of volume on heating, ection in it would not be possible. Notice also that

[1] Lat. *fluere* = to flow. The term includes both liquids and gases.

viscosity (stickiness — Lat. *viscum* = birdlime) is a hindran to convection. That is why jam 'burns' or 'catches' unless is constantly stirred, and why porridge, though quite c on the surface, may be very hot underneath.

An application of convection is seen in the hot-wat supply of a house (Fig. 20/6). The boiler may be behind t kitchen fire, or at the back of a special stove. The heat water passes into a cylinder, from the top of which a pi (branching as required) leads to the h water taps, while an extension, called expansion pipe, leads to a tank in the l which is filled from the main. Cold wa from this tank flows into the cylind and from there into the boiler.

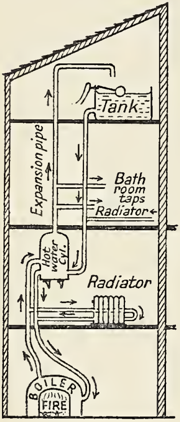


Fig. 20/6

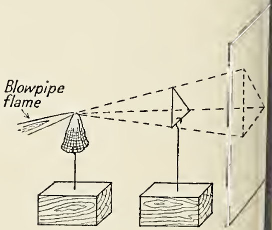


Fig. 20/7

So much for Conduction and Convection. The fact t there must be a third process by which heat is transmit is illustrated by the passage of heat from the sun to the ea Since nearly the whole of the intervening distance cons of empty space, it is clear that we are not concerned w conduction or convection. Let us examine some feature f *radiation*, the name by which this third process is known.

(1) *It travels in straight lines.* This may be shown by experiment illustrated in Fig. 20/7.

Support a small tin triangle (sides an inch or so long) i vertical position. Three or four inches from it support a p of wire gauze that has been folded into a rough cone, p

›wards. Heat the apex with a small bunsen flame, or (better) th the tip of a blowpipe flame. The idea is to obtain, as nearly may be, a point source of heat.

While you are doing this a helper pins a sheet of heat-sensitive per to a drawing-board, and holds it in a vertical position an h or two from the tin triangle, the latter being between the irce of heat and the sensitive paper. The paper soon shows a ite triangular patch surrounded by green. The patch corponds in size and position to the shadow that would have been ained by using a source of light instead of heat.

Assuming that light travels in straight lines, this experiment ws that the same thing is true of heat.

2) *It travels with great speed.* Suppose it is a hot summer's y, and a cloud passes across the face of the sun. The ling effect is felt at once. This shows that heat radiated m the sun must take very little time indeed to travel the e or so that separates the cloud from the earth. (Actually speed is that of light—about 187,000 miles per second.)

3) *Intervening medium not heated.* Even in summer an nan at great heights (if not equipped with special clothing) fers severely from the cold. Heat from the sun is passing *ugh* the air, but without heating it. Similarly, the glass a greenhouse is often much cooler than the air inside— hough the heat must have passed *through* the glass.

Ve should now have no difficulty in understanding the owing definition of ***Radiation***. It is *a process in which heat ransmitted with great speed, in straight lines, and without ting the medium through which it passes.*

t this stage let us summarise our present knowledge.

	Conduction	Convection	Radiation
dium	Solid, liquid or gas.	Liquid or gas.	No material medium.
ange in nedium	Parts maintain same relative positions.	Parts change their relative positions.	
	Rise of temperature.	Rise of temperature.	No rise of temperature.
ed	Greatest in metals, but slow at the best.	Usually greater than conduction. Impeded by viscosity.	Enormous.
ection	Any direction.	Any direction.	Straight lines.

The Solar Spectrum. We have seen that in several i portant respects heat seems to be radiated in the same w as light. In neither case is any material medium requir and in both cases the heat (or light) travels in a straight li Most striking resemblance of all, both travel at the same v high speed. We are driven to the conclusion that the subje of Heat and Light are not fundamentally so different as th appear at first sight. That is indeed the case, and at t point we will recall an experiment which properly belongs the subject of Light, because we shall thereby get a much m thorough knowledge of the nature of Heat. A fuller acco of the experiment is given on p. 260 of our earlier book.

In Fig. 20/8, A is a hole in a shutter through which a narr beam of sunlight enters an otherwise dark room. At B t

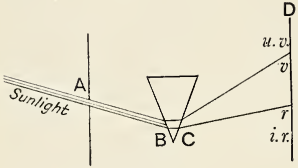


Fig. 20/8

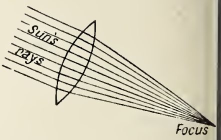
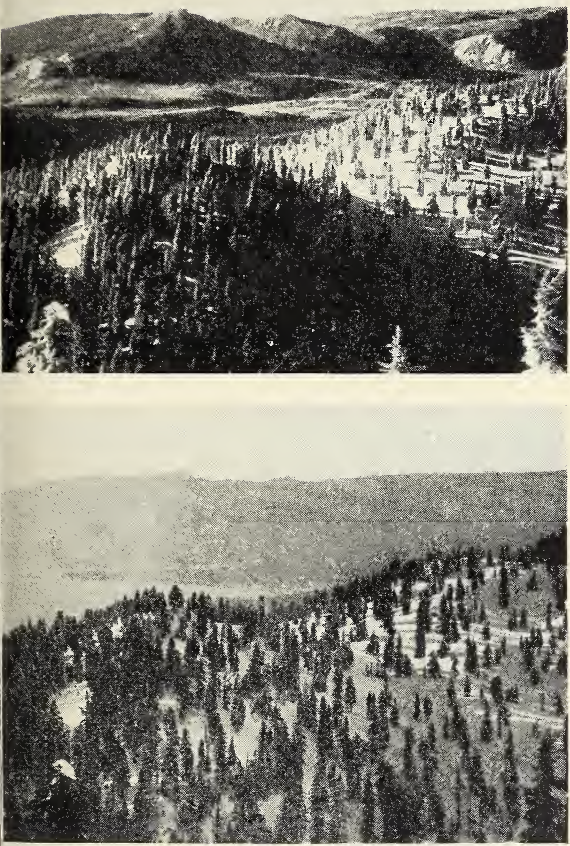


Fig. 20/9

light falls on a prism, where it is *refracted*—i.e. bent out of course—and it is refracted once more when it leaves the pri at C.

Now, the 'white' light of which the beam consists is re a mixture of light of many different colours, and these refracted *unequally*—the red least, the violet most, and ot colours in between. Thus if the light which emerges fr the prism is received on a screen at D, it is found to con of a band of colour known as a *spectrum*, the end nearest apex of the prism being red and the other end violet. S a spectrum would be 'impure'—i.e. the various colours wo overlap. By a suitable arrangement of lenses, however, red rays may all be brought to a *focus* at *r*, the violet ray *v*, and so on; and we obtain a 'pure spectrum.' The 'suit arrangement' will be discussed in connection with Li (Chapter 27).



Photograph by permission of Ilford, Ltd.

'INFRA-RED' COMPARED WITH 'ORDINARY' PHOTOGRAPHY

The different colours correspond to light of different wav lengths. The red waves are about twice as long as the viol but in any case the lengths are so tiny that a special ur called the *micron* (= 1/1000th of a millimetre) is used express them. The red waves have a length of about 0 micron.

What lies on the other side of the red, the *infra-red* (*i* in Fig. 20/8)? Certainly nothing that our eyes can percei By the use of the thermopile, however (see below), and usi a prism and lenses of rock-salt instead of glass, it can shown that a large amount of *heat* falls on this part of t spectrum. Here, then, we have a clue to the nature of h radiation. It is of the same nature as light, differing fr it only in the fact that it is produced by longer waves.

If this is the case, we should expect heat to be subject the same laws of reflection and refraction as light. The f that heat can be refracted is easily shown by using a conv lens as a 'burning-glass.' It gathers rays of heat to a fo just as easily as it gathers rays of light, and in countries wh sunshine is more dependable than in our own, smokers so times carry a small pocket lens with them instead of a b of matches (Fig. 20/9).

The fact that heat is reflected according to the same la as light can also be shown by suitable experiments, thou we shall not discuss them here.

It is worth noticing that as infra-red waves are lon than light waves, they are much more effective than light penetrating a misty atmosphere. That is because particles dust, water, etc., which are large enough to act as obsta to the short light waves, are not able to block the longer inf red ones, and hence the use of the latter in photography (illustration).

The Thermopile. We must now briefly consider the *ther pile*, to which reference was made above.

If rods of two different metals—say copper and iron— soldered together at the two ends, and a difference of te perature is maintained between the two junctions, a curr will flow round the circuit (Fig. 20/10). Now instrume known as *galvanometers* (Chapter 36) are available for det ing extremely small electric currents, and therefore we have

ctrical means of detecting extremely small differences of nperature.

n practice, the metals antimony and bismuth are found give a stronger effect than copper and iron. Further, effect can be multiplied by using a large number of such ctions. The principle is illustrated in Fig. 20/11, where eral pairs of junctions are shown. Fig. 12*a* will give an idea of the struc- e of an actual thermopile. The bars ntimony and bismuth are electrically ılated from one another (except at the

FIG. 20/10

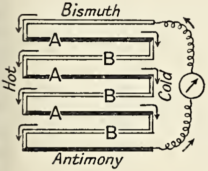


FIG. 20/11

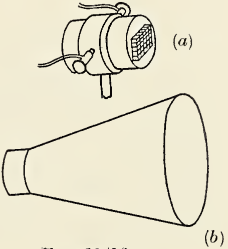


FIG. 20/12

ctions) by strips of mica, and the surfaces intended to ive radiation are blackened. The instrument is often used onnection with a hollow cone, which serves to direct a er amount of radiation on to the absorbing surface.

iffering absorbing powers. A sheet of white paper reflects t of the light that falls on it, and absorbs only a little. when light falls on black velvet, nearly all of it is absorbed, little being reflected.

ommon experience shows that surfaces must act somewhat larly with regard to heat. The metal curb round a fire- e often has a black-leaded iron base with a bright brass The latter is found to be much cooler than the iron , showing that it does not absorb heat so readily. If a or car has been standing in the sun, the black mud-guard be found to be much hotter than the chromium-plated

parts close to it. Generally speaking, light-coloured surfac absorb less radiation than dark ones, and *polishing* a surfa greatly reduces its absorbing power.

Experiments on this subject of absorbing power we carried out as far back as 1805 by the physicist John Lesli His apparatus consisted of (i) an *air thermoscope*, and (what is now known as a *Leslie's cube*. Both are shown Fig. 20/13.

The air thermoscope consists essentially of a U-tube co taining coloured water (or alcohol). The limbs of the tube terminate in two large bulbs, for which inverted flasks are often used.

The 'cube' is a cubical metal box of about 5 inches side, with a removable cap at the top. For our present purpose (comparison of absorbing powers), the four vertical surfaces would have to be exactly similar.

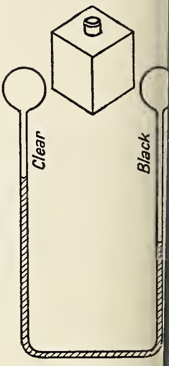


Fig. 20/13

Suppose we wish to examine the effect of *blacking* a surface. One bulb of the thermoscope would be blackened, the other being left clear. The cube, containing water which has just been boiling, would be placed in such a position near the bulbs that an equal amount of heat would be radiated to each. In this case, the liquid below the blackened bulb would be pushed do showing that more heat was being absorbed on that side.

Radiating Power. We have just been considering capacity of different surfaces for *absorbing* heat. We m now think of their capacity for giving it out—their radiat power.

Here again we use a Leslie's cube, but this time the f vertical surfaces are differently treated. One may be cove with lampblack, another varnished, another roughened, the remaining one polished. Instead of the differential thermoscope, we may use the far more sensitive thermop Boiling water is poured into the cube and the cap is repla The water is kept boiling by means of a small bunsen fla

ect heat from the latter being prevented from reaching
thermopile by means of an asbestos screen (not shown).
e various faces are now turned in succession to the thermo-
e, which is connected to a sensitive galvanometer, and the
pective deflections are noted.

Now all the faces are obviously at the same temperature,
it is found that they affect the thermopile very differently.
e lampblacked surface is found to have the strongest
ect. The varnished face comes second, and the rough
face third. The polished face produces very little effect.

On comparing the results of such experiments as this with
se obtained in a preceding paragraph (for absorbing power),
found that *good absorbers* *also good radiators.*

simple but rather striking illustration of this statement may be obtained by ting a piece of china, h a dark pattern on a t ground, into a good fire. We now obtain right pattern on a comparatively dark background. good absorber (dark tern) shows itself to be a

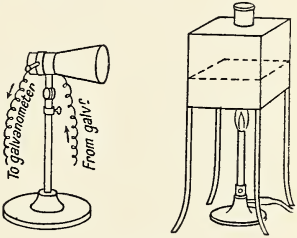


FIG. 20/14

d radiator, while the poor absorber (represented by the t ground) is seen also to be a poor radiator.

ractical applications. It frequently happens that a surface equired to lose as little heat as possible by radiation. It ld be wasteful, for instance, if an electric iron were ating a great deal of its heat into the air. Hence such a ace is brightly polished. Similarly a bright silver tea-pot s little heat by radiation, and so does a thermos flask its silver-coated surfaces.

ot-water pipes and radiators are usually painted a dull k. Really this does not make very much difference, ause (1) a radiator gives off its heat mainly by *convection*, by radiation.

) a *dull* light-coloured surface is not much inferior in ating power to a black one. A bright surface, however

(e.g. when aluminium paint is used), does result in some lo
of efficiency.

The vacuum flask. As a conclusion to our studies in co
duction, convection and radiation we may consider the vacuu
flask, in which devices are adopted for reducing these process
to a minimum. Its essential feature is that it is doubl
walled, with a vacuum between the two walls. A is the point at which the enclosure was sealed off after being exhausted (Fig. 20/15). The outside of the inner wall and the inside of the outer one have been covered with a very thin deposit of silver. The flask is, of course, corked, and for protection is enclosed in a metal case. Chiefly to reduce the risk of breakage from mechanical shock, the flask rests on a cork (or sometimes a spring) placed at the bottom of the metal case.

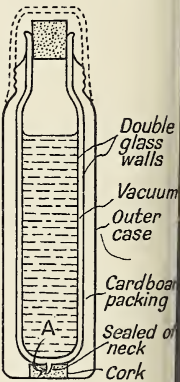


FIG. 20/15

To escape by conduction, heat has to pass to the top of the inner wall—i.e. through a bad conductor (glass) of small cross-section (the glass being thin)—so the rate of loss is very slow.

When the cork is in, the hot liquid is completely cut
from contact with the air, so there is no loss by convection.

The inner vessel loses very little heat by radiation beca
its outer surface is silvered. Of the small amount that d
so escape, the greater part is reflected by the silvered surf
of the outer vessel, very little being absorbed.

When the cork is out, loss of heat by evaporation
convection is considerable, but the remedy is obvious.

Questions

1. A piece of copper gauze is held about an inch abov
bunsen burner. The gas is turned on and lit above the ga
when it continues to burn without lighting the stream of
between the burner and the gauze. Explain. *Oxf.**

2. Describe the Davy safety lamp and explain its mod
action. *Lond.**

3. Describe an experiment to show that copper is a better nductor of heat than iron. *C.W.B.**

4. How would you show that water is a bad conductor of at? *Lond.**

5. Describe and account for the different sensations experienced touching metal and wooden objects in a refrigerator. *Lond.**

6. Draw a labelled diagram to illustrate the heating of a house a hot-water system. Explain the process of heat transference he different parts of the system. *Lond.*

. Why is a better draught obtained with a high chimney than h a short one? *Camb.**

. A piece of thin paper is wrapped tightly round a rod one f of which is metal and the other half is wood. Moving the back and forth through a small flame, it is found that one tion only of the paper becomes charred. Explain. *Dur.**

. Explain what is meant by conduction, convection, and iation.
ive a diagram of a thermos flask, and explain how heat rchange between the contents and the surroundings is imised by its construction.
xplain why a thermos flask works more satisfactorily when three-quarters filled with liquid than when it is filled to hin a short distance of the cork. *Oxf.*

0. Describe an experiment to show that a dull black surface better absorber of heat than a polished surface. *Lond.**

1. Explain what you understand by *radiation of heat*, and ribe an experiment to show how the radiating power of a ace depends upon the nature of the surface. *C.W.B.**

2. Write a short account of the various ways in which heat ommunicated to a room by a fire.
xplain why (*a*) a flame will not pass through a piece of copper ze until the latter becomes red hot, (*b*) loosely woven woollen hing keeps the body warm in comparatively still air but not rong winds. *Dur.*

3. Compare the properties and nature of radiant heat and ble light, and describe two or three illustrative experiments. *Camb.*

CHAPTER 21

MECHANICAL EQUIVALENT OF HEAT

Historical. Robert Boyle, one of the great English scienti of the 17th century, gave much attention to the subject heat. He came to the conclusion that heat might be due the rapid movement of the small particles ('molecules' as should now call them) of which a body is made up. 'Wh for example, a smith does hastily hammer a nail,' he sa 'the hammered metal will grow exceedingly hot, and yet th appears not anything to make it so, save the forcible mot of the hammer, which impresses a vehement agitation on small parts of the iron.'

As the chapter proceeds we shall see that Boyle's vi agree, in broad outline, with those of present-day scienti In the 18th century, however, men went astray. Notic that heat would flow from a hot body to a cold one, they c to the conclusion that heat was a material fluid, to wh they gave the name *caloric*. If a piece of metal is hamme the caloric is squeezed out by the force of the blows. It co to the surface, so to speak, and the metal feels hot.

Some very important observations and experime bearing on this 'caloric' theory, were described by a Co Rumford in the year 1798. He was director of the ars at Munich, and one of his duties was to supervise the bo of cannon. He was very much impressed with the amoun heat produced. According to the theory of that day, cal had been squeezed out of the brass borings. The effect of drilling was to make them less capable of holding heat, as the effect of squeezing a sponge is to make it less cap of holding water.

Rumford therefore made an experiment to compare capacity for heat of the brass borings with the capacit the undrilled brass, expecting to find that the latter greater. (The experiment was something like that descri on p. 169 for finding specific heat.) He could detect difference. Apparently heat was not being squeezed ou the brass. Perhaps it was coming from the air?

Accordingly he arranged an experiment in which boring ok place under water.[1] After two hours and twenty nutes, the water began to boil.

These and other experiments drove Rumford to the con- usion that heat was not a material substance at all. 'Any- ing which any *insulated* body, or system of bodies, can ntinue to furnish *without limitation* cannot possibly be a *terial substance*,' he said, 'and it appears to me to be tremely difficult, if not quite impossible, to form any stinct idea of anything capable of being excited and com- unicated in these experiments, except it be motion.'

In 1799 Davy (the inventor of the lamp) took up the bject. He rubbed together two pieces of ice, with the ult that sufficient heat was produced to melt them. He gued that there are only three possibilities:

The heat must have come either (*a*) from the ice, or (*b*) m the surrounding air, or (*c*) from the motion.

Now, if heat has been squeezed out of the ice, the water oduced should have a smaller capacity for heat than ice. tually its capacity for heat is about twice as great. *That* planation will not do.

To decide whether heat could have come from the air, vy contrived an experiment in which two pieces of ice re rubbed together in the exhausted receiver of an air- mp. They were still melted. Clearly the heat could not ve come from the air.

The only remaining possibility is that heat must be a result the motion, and Davy gave as his verdict that 'Friction ses vibration of the corpuscles of bodies, and this vibration heat.'

Thus Boyle, Rumford and Davy had all arrived at what s really the same conclusion, though we should now speak molecules' instead of 'corpuscles.' That conclusion is still epted.

Further examples. Cases have just been quoted in which etic energy has been converted into heat—the kinetic rgy of a hammer (Boyle), of a rotating drill or borer

[1] This is open to the criticism that the heat may now be coming n the *water*. Davy settled the point far more satisfactorily by nsferring the experiment to a *vacuum*.

(Rumford), of pieces of ice (Davy). We can easily think other examples. Thus a bullet becomes very hot when strikes a target; so do the brake-shoes of a car as they pr against the revolving drum. As we saw a piece of wo both wood and saw become hot. The heat produced pumping up a bicycle tyre is very noticeable; and each o of us could, no doubt, give many more examples.

Conversely, heat may be converted into motion. T motion of water through hot-water pipes and radiators produced by the heat of the boiler fire. Sea-breezes are to land and water being unequally heated by the sun, wh in the steam engine heat from the furnace may cause a hea train to move at sixty miles an hour.

Is there a quantitative relation? Boyle, Rumford and D realised that heat was closely connected with motion, if we think a little we shall see that the motion is not eve thing. If a cannon-ball strikes a target it will produce mu more heat than would a bullet travelling at the same spe It seems, then, that we must take into account the *mass* the moving body, as well as its speed. Now, mass and sp are both included in the term energy (p. 45)—or *mechan energy*, to be more precise. In all the examples we h quoted (the bullet and target for instance) it is mechan energy that is being converted into heat.

Now, mechanical energy can be accurately measu Various units are employed, but quite a common one is foot-pound. Again, heat can be measured, say in Bri thermal units. The question at once arises, *will a g quantity of mechanical energy always give rise to the s amount of heat?*

The work of Joule. In the 1840's a young Manche physicist named Joule pondered the question just sta He devised a number of experiments with a view to answe it, and we will give some account of one of them.

First as to his general principle. Two falling weights we made to turn a paddle which was surrounded by water a suitable vessel (in Fig. 21/1 C and C′ are the weights, and e paddle is inside the vessel E.)

Suppose each weight is 30 lb. and has a fall of 5 ft. Th the work done by a single weight in falling is $30 \times 5 =$ 0

lb. The work done by the *two* weights would, of course, 300 ft.lb., and if they fall not just once, but twenty times, work done would be $300 \times 20 = 6000$ ft.lb.

So much for the work done. Now for the heat produced. Suppose the water in the container weighs 8 lb., and the rise temperature produced by the action of the paddle is 1° hrenheit. Then the amount of heat produced = 8 British rmal units. To produce this, the work that had to be done 6000 ft.lb.

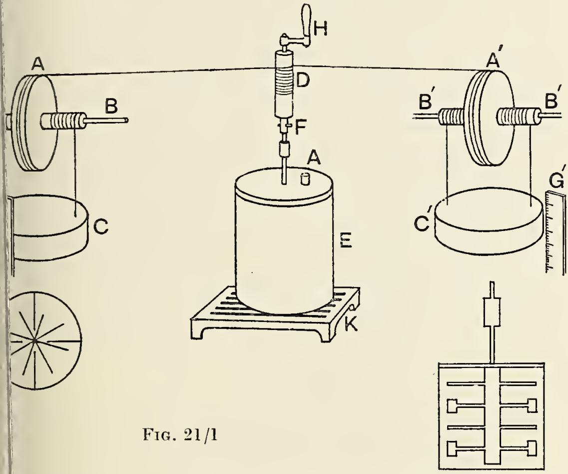


Fig. 21/1

to produce *one* British thermal unit the work required 000 $\div$ 8 = 750 ft.lb.

et us now consider Joule's apparatus and experiment in er more detail.

ne two pulley-wheels AA′ have their axles BB, B′B′ nted in a special way (not shown in the figure), so as to with a minimum of friction. The falling weights CC′ made of lead, and weigh about 29 lb. each. It will be from the figure that as the weights fall they cause the dle D to turn round, and this in turn causes rotation of paddle which is inside the copper vessel E.

The paddle is shown separately on the left and ri (plan and elevation respectively). It consists of eight bla making angles of 45° with each other, and turns throu four 'vanes' fixed to the sides of the vessel. These va have holes cut in them corresponding in shape to the blad and the latter turn through them much as a key turns in t wards of a lock. The vanes serve to prevent the water fr *swirling* as the paddle turns. In other words, the paddle w meet with great frictional resistance as it turns through t water, and the friction will give rise to heat.

When the weights have fallen, the pin F is taken out disconnect the spindle from the paddle. By turning H t weights are wound up. F is then replaced, the weights allowed to fall again, and so on. The distance they fall be read by means of scales G, G′.

The temperature of the water in the vessel was recor by a thermometer which passed through the aperture This thermometer was very sensitive, and Joule was able record changes of as little as 1/200th of a degree Fahrenheit

To reduce loss of heat by conduction, the vessel E st on a wooden grid K. For the same purpose a boxw insertion was placed in the central axle.

Let us now look back to the calculation on p. 209. Th are two very obvious corrections that must be applied if expect to obtain a reasonably correct result.

(i) We must allow for the water equivalent of the m vessel E—really a calorimeter—and of the pad wheel.

(ii) One of Joule's experiments would last about half hour, and during this time the calorimeter would losing heat by radiation (or gaining heat, if temperature of the enclosure was higher than t of the calorimeter). He corrected for this by all ing the calorimeter to remain for another half-h (or whatever the time was), and noting the cha of temperature. From the data thus obtained was able to calculate what the rise of temperat in the actual experiment *would* have been if th had been no loss (or gain) by radiation.

It gives us some idea of Joule's extreme carefulness when we ›tice that he took the trouble to look out a 'spacious cellar' for s experiments, so as to secure uniformity of temperature, and at he placed a large wooden screen between himself and his paratus, so that the temperature of the latter should not be ised by radiation from his body.

He made a number of corrections not mentioned in the general count given above. For instance, he allowed for the weight the string to which his lead weights were attached; and he owed for the fact that his falling weights did not give up *quite* their energy to the paddle. He found that on reaching the or they had a velocity of 2·42 in. per sec., and thus a little ıetic energy was given up to the floor in the form of heat.

Joule devised other experiments besides the one we have scribed, and obtained scores of results. His final conısion was that what we now call 1 British Thermal Unit is uivalent to 772 ft.lb. More recent results, notably by H. A. ›wland, give the value 778. We express this by saying at *the mechanical equivalent of heat is equal to* 778 *ft.lb. per itish Thermal Unit.*

In honour of Joule, the mechanical equivalent is usually noted by J—i.e. J = 778 ft.lb. per British Thermal Unit.

To raise the temperature of 1 lb. of water by 1° C. requires, course, 9/5ths as much heat as to raise it 1° F.—i.e. the .-degree C.' unit is 9/5ths as large as the lb.-deg. F. unit B.Th.U.).

$\therefore$ the value of J in lb.-degree C. units is $778 \times \frac{9}{5} = 1400$.

Let us find the value of J in the 'c.g.s.' system of units, given ıt 1 lb. = 454 gm. and 1 ft. = 30·5 cm.

778 ft.lb = work done in raising 778 lb. through 1 ft.
= work done in raising 778 × 454 gm. through 30·5 cm.
= work done in raising 778 × 454 × 30·5 gm. through 1 cm.
= 10,800,000 centimetre-grams (approx.)
= 10,800,000 × 981 ergs (p. 41)
= 1060×10^7 ergs (approx.).

Again, 1 B.Th.U.
= heat required to raise temperature of 1 lb. of water by 1° F.
= heat required to raise temperature of 454 gm. of water by 5/9° C.
= heat required to raise temperature of $454 \times \frac{5}{9}$ (= 252) gm. of water by 1° C.
= 252 calories.

P

Thus instead of saying

$J = 778$ ft.lb. per British Thermal Unit we may say

$J = 1060 \times 10^7$ ergs per 252 cals.

$= \frac{1060}{252} \times 10^7$ ergs per cal.

$=$ **$4{\cdot}2 \times 10^7$ ergs per calorie.**

Summarising the various ways in which the value of may be expressed, we have:—

$J =$ **778** ***ft.lb. per British Thermal Unit***

$=$ **1400** ***ft.lb. per lb.-deg. C.***

$=$ **$4{\cdot}2 \times 10^7$** ***ergs per cal.***

$=$ **4·2** ***Joules per cal.***

(a Joule being defined as 10^7 ergs).

Why Joule's work is outstanding. One could name mar men in the 19th century who carried out numerous experimen with the utmost patience and accuracy. But Joule's wo is regarded as quite specially important. Why?

There are in science certain great *generalisations*—trut which may be simple, but which are of very wide applicatio They apply to everything in the world and sometimes everything in the universe. One of these generalisations Newton's law of gravitation. We have to take it into accou whether we are trying to explain the fall of an apple or t motion of a planet. Another is the theory of evolution p forward by Charles Darwin, which has thrown light on thousand problems applying to all life on the earth, proble which would otherwise have been utterly baffling.

Still another is the principle of the 'Conservation of Energ —the principle that energy can be neither created n destroyed, though it may be converted from one form in another. Apparently it applies to the whole universe. we have seen, Joule showed that there was a very exa relationship between mechanical energy and heat. By oth experiments he showed that there was a similar relationsh between chemical energy and heat, and between electrical ener and heat. Thus his work gave a firm basis for the Princi of Conservation of Energy, and it is because that princi is one of the great generalisations of science that the work Joule is regarded as being of quite outstanding importanc

Laboratory Methods. We shall describe two laboratory ethods for finding J.

(i) The falling lead-shot method.
(ii) The rotating drum method.

(i) *The falling lead-shot method.*

A cardboard tube AB about a yard long and 3 or 4 in. wide corked at both ends, and about 4 lb. of lead-shot is introıced (C). The temperature of the shot is taken ith a sensitive thermometer. The tube is then ımpletely inverted for a definite number of times, y 100, and the temperature is then taken again. ıe average distance fallen by each lead-shot must so be measured (it is represented by h in Fig. 1/2). We will take it that the specific heat of ad is known ($= 0{\cdot}031$). For our unit of heat we ll take the pound degree-Centigrade unit, i.e. the nount of heat required to raise the temperature of pound of water by 1° C.

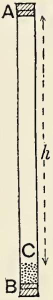


FIG. 21/2

Suppose that in a given experiment $h = 3{\cdot}25$ ft.
Initial temperature of lead-shot $= 14{\cdot}72°$ C.
Final ,, ,, ,, $= 18{\cdot}89°$ C.
No. of falls $= 100$.

The weight of the lead-shot need not be known. ll it w lb. Then—

Work done by w lb. of lead, falling 3·25 ft. $= 3{\cdot}25w$ ft.lb.

$$\therefore \quad \text{work done in 100 falls} = 3{\cdot}25w \times 100 \text{ ft.lb.}$$
$$= 325w \text{ ft.lb.}$$

Heat produced = heat required to raise temperature of w lb. lead by $(18{\cdot}89 - 14{\cdot}72)°$ C., i.e. by $4{\cdot}17°$ C. This amount is)31 $\times w \times 4{\cdot}17$ units.

$\therefore$ $0{\cdot}031 \times w \times 4{\cdot}17$ units of heat are produced by $325w$ ft.lb.

$$\therefore \text{ 1 unit of heat is produced by } \frac{325w}{0{\cdot}031 \times w \times 4{\cdot}17}$$
$$= 2514 \text{ ft.lb.}$$

As the correct answer is 1400, this result is absurdly high, e important source of error being that, at every inversion, ıch of the lead shot falls before the tube has reached the rtical position. However, the experiment helps to fix the ɘa of a quantitative relation between work and heat, and has the advantage of great simplicity.

The following method gives much more accurate results:-

(ii) *The rotating-drum method.*

The apparatus consists of a brass drum which can be turn- by means of a handle. As it turns, it presses against a brak consisting of a silk ribbon, kept tight by a known weight attached to its lower end and a spring balance pulling at its upper end. The weight (say w gm. wt.) is balanced by the frictional force (f gm. wt.) between drum and ribbon, *plus* the pull (s gm. wt.) of the spring balance; i.e. $w = f + s$, and so $f = w - s$.

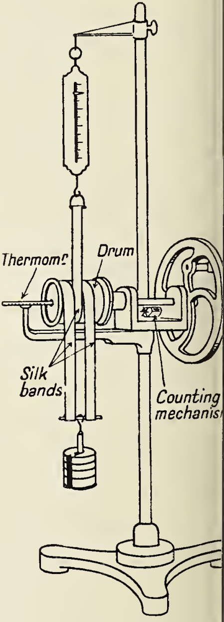


FIG. 21/3

As silk is a bad conductor, not much of the heat produced on its inner surface is lost by passing outwards—nearly all of it passes inwards through the drum (made of good conducting material) to a known weight of water contained within. The temperature of this water is taken by a bent thermometer, which passes through a hole in the drum.

To carry out an experiment, we put a measured quantity of water into the drum by means of a burette, and read the thermometer. (This has a very open scale reading to 0·01° C.). We then turn the handle several hundred times at a speed sufficient to keep the weight floating and to maintain the reading of the spring balance about the centre of the scale. Suppose this reading is 160 gm and the hanging weight is 700 gm., then as already explaine to turn the drum it is necessary to overcome a frictional for of 700 – 160 or 540 gm. In *one* turn the work done again this force of friction is 540 × C centimetre-grams. where

the circumference of the drum measured in centimetres. o find the total work done we must multiply by the number f turns recorded by a counter included in the instrument.

Of the heat produced, some goes into the drum as well as to the water, so we shall have to find the water equivalent the drum.

We shall now be able to follow the working out of results such might be obtained in an actual experiment.

Mass of brass drum (given) . . .	272 gm.
Circumference of drum	23·5 cm.
Water added = 50 c.c.	50 gm.
Specific heat of brass	0·092
Initial temperature of water . . .	15·26° C.
Final ,, ,, . . .	16·83° C.
∴ Rise of temperature	1·57° C.
No. of revolutions	400
Lower weight	700 gm.
Reading of spring balance (average) .	160 ,,

ork done = $(700 - 160) \times 23{\cdot}5 \times 400 = 5{\cdot}08 \times 10^6$ cm.-gm.
eat produced = $(50 + 272 \times 0{\cdot}092) \times 1{\cdot}57 = 118{\cdot}0$ cals.

$\therefore \quad 118$ cals. $= 5{\cdot}08 \times 10^6$ cm.-gm.

$\therefore \quad 1$ cal. $= 4{\cdot}31 \times 10^4$ cm.-gm.

. Mechanical equivalent of Heat $= 4{\cdot}31 \times 10^4$ cm.-gm. per cal.

By working through calculations such as the following e shall improve our grip of the fact that a given amount mechanical energy is equivalent to a definite amount of heat.

Example 1. *By how much should the temperature at the bottom Niagara Falls (height 167 ft.) exceed that at the top?* ($J = 778$ *ft.lb. r B.Th.U.*)

The rise of temperature will be the same whatever weight of ter we consider,[1] so for simplicity let us consider 1 lb.

Work done by 1 lb. of water falling 167 ft. = 167 ft.lb.

778 ft.lb. produce 1 B.Th.U.

$\therefore$ 167 ,, ,, $\frac{167}{778}$,,

Now 1 B.Th.U. would cause temp. of 1 lb. of water to rise 1° F.

$\therefore \quad \frac{167}{778}$ B.Th.U. make it rise $\frac{167^\circ}{778}$ F. = **0·21° F.** or **0·12° C.**

(N.B. Water falling over rocks would lose much of its kinetic ergy en route, by friction against the rocks, which would ceive a large part of the heat produced. Cf. next example.)

[1] Cf. the lead shot experiment (p. 213) in which the w's cancel.

Example 2. *A brick weighing 9 lb. slides 12 ft. down a roug plank inclined at 30° to the horizontal, and acquires a velocity o 10 ft. per sec. How much heat is produced?*

The *vertical* height through which the brick has fallen is 6 ft (easily shown by geometry).

$\therefore$ work done by gravity $= 9 \times 6 = 54$ ft.lb.

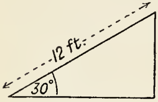


Fig. 21/4

At the bottom of the plane, the kineti energy actually possessed by the brick ($\frac{1}{2}mv$ is $\frac{1}{2} \times 9 \times 10^2 = 450$ ft.pdls.

$= 450 \div 32$ ft.lb. $= 14{\cdot}1$ ft.lb.

The difference $54 - 14{\cdot}1$ or $39{\cdot}9$ ft.lb. repr sents the energy which has disappeared as he (the result of friction between the brick an board).

Now 1400 ft.lb. = 1 unit of heat (lb. deg. C.)

$\therefore$ 39·9 „ $= \dfrac{39{\cdot}9}{1400}$ or **0·0285 unit.**

Example 3. *A stationary engine burning $37\frac{1}{2}$ lb. of coal per ho is able to pump water to a height of 490 ft. at the rate of $62\frac{1}{2}$ gall per minute. Find the efficiency of the engine (1 lb. of the co gives 7000 lb.-deg. C. units; 1 lb.-deg. C. = 1400 ft.lb.; 1 ga = 10 lb.)*

(a) *Heat produced per minute.*

Coal burnt per hour $= 37\frac{1}{2}$ lb.

$\therefore$ heat produced per hour $= 37\frac{1}{2} \times 7000 = 262{,}500$ uni

$\therefore$ „ „ „ min. $= 262{,}500 \div 60$

$= 4375$ units.

(b) *Work equivalent to this heat.*

1 unit = 1400 ft.lb.

$\therefore$ 4375 units $= 4375 \times 1400$ ft.lb.

(c) *Work actually done per minute.*

$62\frac{1}{2}$ galls. (= 625 lb.) is raised 490 ft.

$\therefore$ work done $= 625 \times 490$ ft.lb.

(d) *Efficiency.* This is the percentage that (c) is of (b).

$$\therefore \quad \text{efficiency} = \frac{625 \times 490}{4375 \times 1400} \times 100$$

which works out to **5%.**

Joule. James Prescott Joule was so outstanding a figure ı the history of 19th-century Physics that we ought to know ›mething of his life.[1]

He was born at Salford near Manchester on Christmas Eve ³18. As a boy he was considered rather too delicate for ·dinary school life, and so he was educated at home until ıe age of sixteen. Soon afterwards he studied geometry ıd chemistry under John Dalton. Maybe he caught some-ing of Dalton's independent scientific outlook. Certainly is interesting to note that one of the century's greatest ıysicists should have studied under one of its greatest emists.

In his early twenties he was much interested in the 'electro-agnetic engine' (i.e. the electric motor), and he tried to ›asure its power by the rate at which the magnets contained it would lift a weight. Later he realised that the amount work he would get out of his 'engine' was closely related the consumption of zinc in the battery; in other words, saw that mechanical energy might be the equivalent of a finite amount of chemical energy. Before he was twenty-e he had a very clear grip of the problem that was to minate his life—the quantitative relationship between ·chanical energy and heat. The 'paddle-wheel' experiment eady described is only one of a number of methods which devised in his attempt to solve the problem. It was ·ried out in 1845.

Γhe idea that a given amount of mechanical work could converted into a definite quantity of heat was a new one, l, like most new ideas, it had a somewhat chilly reception. is is very clear from what happened in 1847. Joule was read a paper on the subject to a section of the British sociation which in that year met at Oxford. Time was her short and (writes Joule) 'the chairman suggested that hould not read my paper but confine myself to a short ·bal description of my experiments.'

A sure sign that the chairman did not consider the paper ›e of much importance !

[1] For most of the particulars in this paragraph the writer acknow-;es his debt to 'Joule and the Study of Energy,' by A. Wood ›lished by Bell).

By courtesy of the Manchester Literary and Philosophical

James Prescott Joule

'This I endeavoured to do,' Joule continued, 'and discussion ot being invited, the communication would have passed ithout comment if a young man had not risen in the Section, nd by his intelligent observations created a lively interest n the new theory. The young man was William Thomson' ater the famous Lord Kelvin).

It is interesting to read Lord Kelvin's account of the same ncident. 'I can never forget the British Association at xford in 1847,' he says, 'when in one of the sections I heard paper read by a very unassuming young man, who betrayed o consciousness in his manner that he had a great idea to nfold. I was tremendously struck with the paper. I at rst thought it could not be true, because it was different om Carnot's theory, and immediately after the reading of e paper I had a few words with the author, James Joule, hich was the beginning of our forty years' acquaintance nd friendship.'

'Very unassuming,' says Kelvin, and like most truly great en, Joule was essentially humble. Writing to his brother 1887 he writes, 'I believe I have done two or three little ings, but nothing to make a fuss about.' He died in 1889, nd in Westminster Abbey, near the burial places of Lord elvin and Sir Isaac Newton, there is a tablet to his memory.

Questions

A

1. Give *three* everyday examples of the conversion of work to heat.

2. Give *two* examples of the conversion of heat into work.

3. How many British thermal units are equivalent to 7780 lb.?

4. (*a*) An engine is working at 10 h.p. How much work is ne in one minute? (Answer in factors.)

(*b*) If this work were all made to pass as heat into a gallon of ter (= 10 lb.) by how much would the temperature be raised?

B

1. Describe a non-electrical method of finding the relation tween work and heat, and define the units of work and heat nployed.

A steam plant, burning 0·5 lb. of coal per minute, suppli steam to a steam engine. If the overall efficiency of the syste is 25%, determine the horse-power generated by the stean engine. The calorific value of the coal = 14,960 B.Th.U. p lb., the mechanical equivalent of heat = 780 ft.lb.wt. p B.Th.U., and 1 h.p. = 33,000 ft.lb.wt. per min. *C.W.B.*

2. A man walks up a flight of stairs 10 metres high. If ha the energy which he expends is converted into heat, how mu would you expect his temperature to increase if there were n natural mechanism for keeping it constant?

(1 cal. = 4·2 joules. Assume that the heat capacity of human body is the same as that of an equal mass of wate $g = 981$ cm. per sec.^{2}) *Camb.**

3. The *mechanical equivalent of heat* is 778 *ft.lb. per Briti Thermal Unit*. Explain this statement carefully, defining th terms printed in italics.

A load of 74 lb. is raised 3 ft. vertically by means of a machi whose efficiency is 22·2%. Assuming that the portion of th work done by the effort that is apparently wasted eventual reappears as heat, calculate the number of B.Th.U. produce *Oxf.*

4. If all the heat which is given out by 1 kg. of steam in co densing to water at 100° C. is converted into work, how ma joules will be produced? If the work is done in 1 minute, wh is the average power produced? (Latent heat of steam = 5 cals. per gm.; mechanical equivalent of heat = 4·2 joules p cal.) *Camb.*

5. Water flows over a waterfall 30 metres high, and at the fo of the fall it drops into a pool where it may be regarded stationary. What is the difference in temperature between t water at the top and that at the bottom of the fall?

(1 cal. = $4{\cdot}2 \times 10^7$ ergs, $g = 981$ cm. per sec. per sec.) *O.C.**

6. 100 gm. of lead shot is allowed to fall 50 times through tube 1 metre in length and is then dropped into 20 gm. of wat the temperature of which is raised 0·59° C. Assuming that the mechanical energy is converted into heat, calculate t mechanical equivalent of heat in ergs per calorie. *O.C.**

CHAPTER 22

LIGHT—PROPAGATION AND REFLECTION

A. *Propagation*

'E have many reminders in everyday life that light travels straight lines. We notice the straight beam from the eadlight of a car, from a cinema projector, or the humble ectric torch. A burly individual keeping his hat on at ie pictures can very effectively obstruct the view of the ilucky person sitting behind—the light is unable to travel *und* him; and an umpire giving an l.b.w. decision at cricket unconsciously perhaps, assuming the principle in question.

A very simple experiment illustrating the point was scribed in our earlier book. We had three pieces of card- ard, A, B, C, in which were bored three small holes, P, Q

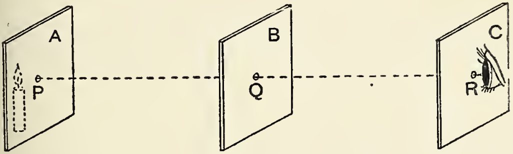


FIG. 22/1

d R, respectively, brought into line by stretching a thread rough them. A lighted candle was then placed to the left P, and observed by an eye placed to the right of R. The me is visible, but becomes invisible if Q is displaced slightly one side. This shows that light can travel along the path QR only when that path is a straight line.

We also studied the *pinhole camera*. The image is inverted cause of the crossing, at the pinhole, of the rays of light ich form it. If A (Fig. 22/2) is enlarged, more light enters

and a brighter image is obtained. The image, however, i not so sharply outlined. That is because the one large hol may be regarded as equivalent to several small holes ver close together. Each of these would produce an image, bu the various images would be in slightly different position

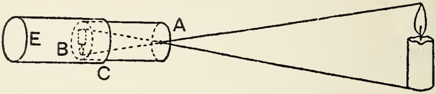


FIG. 22/2

(cf. Fig. 22/3, where two such small holes are represented Thus the outline is confused.

If the distance from candle to pinhole is increased the imag becomes smaller. This result easily follows from simila triangles, for if i = length of image and o = length of objec while x = distance of image from pinhole and y = distanc of object (Fig. 22/4), then $\frac{i}{x} = \frac{o}{y}$, or $i = x \times \frac{o}{y}$. Clearly if w increase y, we reduce i.

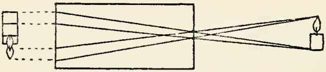


FIG. 22/3

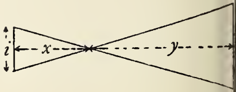


FIG. 22/4

The *shape* of the hole makes no difference so long as it small. If the hole is circular, the image will be made up a vast number of circular patches—one circular patch f each point on the object. If it is triangular, the image w be made up of a vast number of triangular patches. It is though a painter filled in an outline with a multitude of ti circular patches of paint. He would get the same result the patches were of triangular or any other shape—so lo as they were very small.

Lastly, in our earlier work we studied eclipses of the s and moon. Fig. 22/5 represents an eclipse of the sun caus by the moon B coming between the sun A and the ear

ACTION OF THE PINHOLE CAMERA
From a drawing in Guilleman's 'Forces of Nature'

pposed to be situated at M or N. The earth's distance n the sun is not always the same).

'he shadow of the moon is seen reaching to C. If the h is near enough for this shadow to touch it (Fig. 22/6), tal eclipse will be observed over a small circular patch rer more than 190 miles in diameter). Chiefly owing to

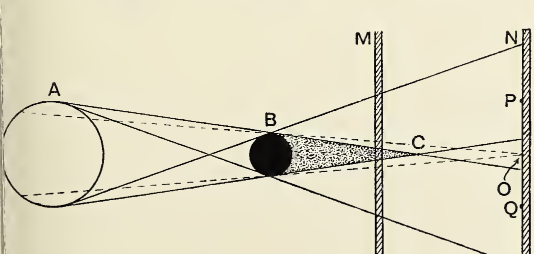


FIG. 22/5

the moon's motion, this circular patch moves over the eart surface, so that the eclipse is observed first at one part a then another of a track which may be 190 miles wide.

If the earth is beyond the point C, a total eclipse will not be visible at any part of it. At a point such as O, however (Fig. 22/5), between the two 'tangent' lines, only the outer rim of the sun will be observed—i.e. there will be an *annular* eclipse. At P only the top part of the sun will be visible, and at Q only the bottom part—i.e. at these points partial eclipses will observed.

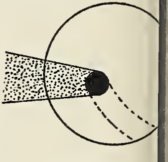


FIG. 22/6

An eclipse of the moon is produced when the earth co between the sun and the moon, with the result that its shad is cast on the moon. Fig. 22/5 will still serve as our illust tion, if we now understand that A is the sun and B the ea while M represents the position of the moon. In this ca however, the moon is always well on the 'umbra' side of In the course of its journey round the earth, it happ sometimes that the moon moves into the space represen by the shading in Fig. 22/5. We soon have the appeara

(a) (b) (c)

FIG. 22/7

shown in Fig. 22/7 (*a*), then, later, (*b*) and (*c*), and fin the moon is entirely covered by the earth's shadow. Actu the shadow is not completely black. That is because, tho the rays of the sun cannot reach the moon by a *straight* pa some of them manage to reach it by a *curved* one (owing refraction by the earth's atmosphere). The only 'success rays are those of greatest wave-length, the red and yel ones; hence the moon appears as a copper-coloured disc.

From an examination of Fig. 22/8 it should be clear t

ı eclipse of the sun can occur only when the moon is in the ew moon' position, and an eclipse of the moon only when is in the 'full moon' position.

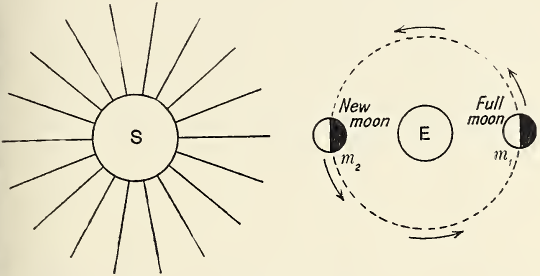


FIG. 22/8

Velocity of Light. One often meets with references to the locity of light. This has been determined by a number methods of which we shall indicate one or two.

The first dates back to the year 1676, and is not at all ficult to understand. The planet Jupiter (J_1 or J_2 in g. 22/9) possesses a number of 'moons' or satellites, of ich, however, we are conned only with one, M_1 or . At regular intervals this ellite passes into the shaw cast by Jupiter, and is en eclipsed. The young nish astronomer Olaf mer noted the exact time it elapsed between one ch eclipse and the next tually it was 42 hr. 28 n. 36 sec.), and it was then imple matter to forecast the exact time at which eclipses uld occur for months ahead—or at least so Römer thought. Six months later, however (Jupiter being at J_2 and the th at E_2), he found that instead of Jupiter's satellite being

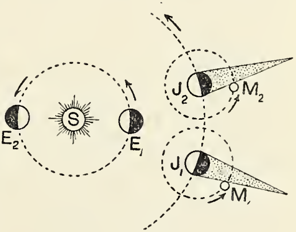


FIG. 22/9

eclipsed at the calculated moment, it was 'behind time' 16 min. 36 sec.! He was very surprised at first, but after little hard thinking he hit upon the reason. His first observ tions were made when the earth was, say, at E_1. Six mont later the eclipse would have occurred at the exact time calculated *if the earth had remained at* E_1. But in this months the earth had moved to E_2, right at the other e of the diameter of its orbit, a distance of about 186 milli miles. The eclipse was 16 min. 36 sec. late because lig had taken that time to make its long journey of 186 milli miles. We can easily calculate the velocity, for if light tal

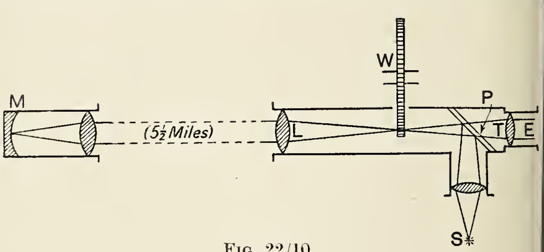


FIG. 22/10

16 min. 36 sec. (= 996 sec.) to travel 186 million miles, t distance travelled per second is 186,000,000 ÷ 996 or nea 187,000 miles.

In 1849 Fizeau employed an ingenious method in wh he made use of a toothed wheel revolving at high speed. apparatus extended from the village of Suresnes, near Cloud (outside Paris) to Montmartre, a suburb of Paris distance of 8·633 kilometres or about $5\frac{1}{2}$ miles.

At Suresnes is S, a source of light. The light was m to strike on the sheet of plate glass P, and then to through the space between two teeth of the wheel W. A passing through the lens L it goes on its $5\frac{1}{2}$-mile journey the mirror M (at Montmartre), from which it is reflected b along its original path. Some of the reflected light pa through the plate glass into a lens T, and reaches an placed at E. To the observer thus placed, the source light S appeared like a star.

Now, by making the wheel revolve at a certain speed, it as found that S ceased to be observed. We can see what as happened. The *space* through which the light had assed on its outward journey is now occupied by a *tooth*, wing to the movement of the wheel. By doubling the speed ie light was made to reappear—it was coming back through ie *next* space. At treble the speed the light was eclipsed ice more, and so on.

The wheel contained 720 teeth and 720 spaces, and the st eclipse occurred when it was making 12·6 revs. per sec. e must calculate the time for it to move forward a distance 'one tooth.'

One tooth occupies $\frac{1}{2 \times 720}$ or $\frac{1}{1440}$th part of the circumrence.

Time required for 1 revolution $= \frac{1}{12 \cdot 6}$ sec.

time required to move forward 'one tooth' $= \frac{1}{12 \cdot 6 \times 1440}$ sec.

this time light has travelled *twice* the distance from W to M, . 2 × 8·633 or 17·266 km.

$$\begin{aligned} \text{no. of km. per sec.} &= 17 \cdot 266 \times 12 \cdot 6 \times 1440 \\ &= 313{,}000 \text{ km. per sec.} \\ &= 195{,}000 \text{ miles per sec.} \end{aligned}$$

(Fizeau's result was about 5% too high.)

A year later—i.e. in 1850—Foucault made experiments in hich he used a revolving mirror instead of a revolving wheel, it we will not describe his method here. Since then the oblem has been attacked by a number of different workers ing very ingenious methods. Some of the best results were tained by the great American physicist A. A. Michelson 852–1931), who found the velocity to be 186,271 miles per cond. For most practical purposes it is sufficient to member the number as 186,000.

At this enormous speed, light could travel a distance equal the earth's circumference in rather less than one-seventh a second. The sun is so distant, however, that light avelling from it takes about $8\frac{1}{3}$ min. to reach us. If we

could flash a light signal to Jupiter and have it instantl returned, we should receive our reply in about $1\frac{1}{2}$ hr.

Once outside the solar system, these distances and tim are enormously increased. The *nearest* fixed star, Alpl Centauri, is at such a distance that light from it takes 4 *years* to reach us, while for the Pole Star the time is 55 year In fact, if an observer on the Pole Star could witness even on the earth by means of a telescope, he would in 1952 b witnessing the Queen Victoria Diamond Jubilee celebratio of 1897.

To express such distances the astronomer often uses a un known as the *light-year*, this being the distance that ligl would travel in one year (it comes to about 6 million milli miles). Thus the distance of the Pole Star is 55 light-yea That of some of the spiral nebulae is about 100 million lig years—but confronted with such magnitudes our imaginatio are helpless.

B. *Reflection*

Reflection in Nature. There are a few objects, such as t sun, a candle flame, a fire, etc., which are *self-luminous* we see them by their own light. The vast majority, howeve are seen by the light which has first fallen on them from self-luminous body, and has then been thrown off or *reflect* It is interesting to think for a few minutes of the changes should notice if there were no such thing as the reflection light. We should see the sun and the stars, but the s between them would be inky black, and we should see nothi whatever of the moon or the planets which shine by reflect light. It would be useless to go to school. If lights we switched on we should see them, but we should be unal to see the teacher, or the blackboard, or our books; and should be constantly colliding with other people because should be unable to see them either. You can trace out a f other consequences for yourself. Life could certainly n continue for very long in a world where no light was reflect

Laws of Reflection. In our earlier book we considered t *laws* of reflection, which are so important that we mu recapitulate them here. They are—

1. *The angle of reflection is equal to the angle of incidence.*
2. *The reflected ray lies in the plane containing the incident ray and the normal.*

These laws can be proved by means of the ray-box (*Junior ysics*, pp. 211–12). A proof in which we use pins instead a ray-box is perhaps less interesting, but is in fact more act.

Experiment 1. Place a rectangular strip of mirror glass AB, 6 in. × 1 in., on its edge on the bench, lying on a sheet of per. (It is convenient to have the mirror glued to a block of od CD which keeps it from falling over.) Stick two pins P, upright in the paper, and place two other pins R, S in such a sition that they 'cover' P′ and Q′ (P′ and Q′ being the images P and Q respectively).

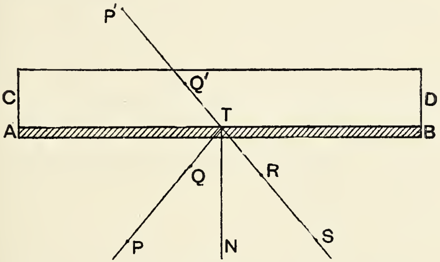


FIG. 22/11

Now PQ represents a ray of light striking the mirror. After ection, we see the pins in the direction P′ Q′ (this direction ng marked by the pins R and S). This means that the ray ight which reached the mirror by the path PQ has left it by path RS. With a pencil, draw the outline of the mirror, l then remove it.

oin PQ and SR and produce them to meet at T. It will be nd that T is on, or very near, the back of the mirror, from which reflection has taken place. From T draw the normal TN, l carefully measure PTN and STN, the angles of incidence and ection respectively. Repeat the experiment for various angles ncidence.

)ur experiments show clearly that the angles of incidence l reflection are equal. Further, consider the points P, at which the pins enter the paper. PQ represents an

incident ray which grazes the paper—i.e. the ray is *in th plane of the paper.* So is the normal TN. Now P′Q′, th bottom ends of the 'image' pins, are also seen in this sam plane. Thus we may say that incident ray, normal an reflected ray all lie in the same plane.

Image behind mirror. When a man stands in front of plane mirror, his image *seems* to be as far behind the mirr as he himself is in front of it. It can easily be shown b experiment that this is actually the case. In this experimer we make use of what is called the *method of parallax*, whic you can quickly illustrate for yourself. Hold your fountai pen A about a foot in front of your face, and your pencil about 6 in. beyond the pen. Now move your head fro side to side. The pen seems to move faster than the penc Interchange these positions. Now, of course, the pen seems to move faster than the pen. Next make A touch B and move your head once more. This time A and B ke together. Let us put the matter the other way roun When A and B keep together as you move your head, th are in the same position.

All this, of course, is extremely simple, but the princip is often useful, and will enable us to 'fix' the position of a image behind a mirror.

Experiment 2. Place the rectangular mirror on its edge as Expt. 1, and stick a pin A in the bench, vertically, about 6 i in front of it. Now place a second pin behind the mirror so that you can see its upper part, and so that it seems to coincide with the image of A. Move your head to see if there is any apparent separation between the real pin and the image. If so, alter the position of the second pin until, on moving your head, pin and image keep together. The second pin is now in the position occupied by the image of the first one.

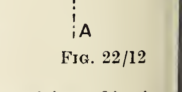


Fig. 22/12

Suppose A is the first pin and B is the position of its ima which we have now found. Draw a line PQ to show t position of the (back) reflecting surface of the mirror. Jo AB cutting PQ in X. We find that XA = XB, and that A

perpendicular to PQ. Thus *if an object is placed in front of plane mirror, the line joining it to its image will be at right gles to the mirror; and the image will be as far behind the rror as the object is in front.*

It is quite easy to prove geometrically that this result lows from the laws of reflection.

Let A be the pin, PQ the reflecting surface (Fig. 22/13). AC any ray of light proceeding from A and striking the mirror. aw the normal CN, and construct the reflected ray CR making the angle NCR = angle NCA.

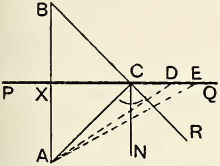


Fig. 22/13

Fig. 22/14

)raw AX perpendicular to the mirror, and produce AX RC to meet at B. You should have no difficulty in ving that the triangles ACX and BCX are congruent, that XB = XA—i.e. a ray of light AC, after reflection n the mirror, travels in a direction that (produced back-ds) passes through the fixed point B, where B is so placed t XB = XA and that AB is perpendicular to PQ.

ut what has been proved to be true with regard to AC is e of any other ray, such as AD or AE.

herefore *all* rays coming from A, after reflection, will el as though they came from B—i.e. the image of A is a it B so placed that AB is at right angles to the mirror, that B is as far behind the mirror as A is in front of it.

) far the reflections we have considered have been from e surfaces only. We must now consider what happens n the surface is curved.

ı our earlier book we saw that a curved surface may be *ave* or *convex*. We can easily remember which is concave, use such a surface presents a *cave* or hollow to the observer. inside of a spoon (C in Fig. 22/14) would be an example.

If a curved surface bulges towards the observer (V in t same figure) it is said to be convex.

A concave or convex *spherical* surface is one which for part of a sphere, and it is with such surfaces (forming mirr that we shall be chiefly concerned in this chapter.

We must recall one or two other terms. The ***centre curvature*** of a mirror is *the centre of the sphere of which mirror forms a part* (C in Fig. 22/15). The middle point

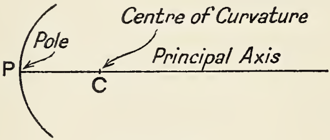


FIG. 22/15

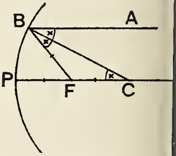


FIG. 22/16

the surface is known as the ***pole*** of the mirror, and the joining the pole of the mirror to the centre of curvature, produced, is known as the ***principal axis.***

Principal focus. Suppose a ray of light AB, travell parallel to the axis, strikes a concave mirror at B (Fig. 22/ Although the mirror is curved, we may take it that an *exceedi small* portion at B is flat, its direction being at right an to the radius BC. Thus by the ordinary law of reflect the ray AB will be reflected along BF, where $\angle CBF = \angle C$ Suppose this reflected ray cuts the principal axis in F. T by parallels, $\angle FCB = \angle CBA$.

But as already seen, $\angle CBF = \angle CBA$

$$\therefore \quad \angle CBF = \angle FCB$$

$$\therefore \quad FB = FC.$$

Now *if AB is very close to the axis*, B will be very clos P, and FB will be very nearly equal to FP.

But $$FB = FC$$

$$\therefore \quad FP = FC.$$

i.e. F is the middle point of CP.

Thus the ray AB after reflection passes through the mi point of CP. The same thing can be proved of *all* rays w before striking the mirror were parallel to the principal

l so all such rays are brought to a *focus* at F. This point s known as the ***principal focus*** of the mirror.

Notice again, however, that the rays we have been speaking out—rays parallel to the principal axis—will pass through *only if they were originally close to the principal axis.*

Caustic Curves. A pretty and interesting experiment can carried out by making use of rays which are *not* all close the principal axis. The mirror ACB may conveniently sist of a rectangular sheet of bright metal bent into a ni-circle. It stands upon a sheet of paper. Facing it at ttle distance is a ray-box with a graining nb in front of the lens. The lamp is ved forwards or backwards until the ght lines on the paper are parallel. parallel 'rays', EG, HK, etc., are reted by the semi-circle of metal, and rise to a 'caustic curve' on the sheet aper.

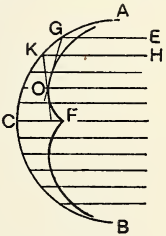


Fig. 22/17

Let us think of the point O at which two secutive 'rays,' EG and HK, after being ected from the mirror, cross one another. ause rays are crossing at O there is e concentration of light there—it is a sort of focus. er pairs of consecutive rays form other foci, and it can found by careful drawing that all these foci lie along a liar curve—the *caustic curve* of which we have just ken. All the reflected rays are tangents to it. It con- of two parts with a specially bright 'cusp' or prominence '. This cusp is the focus of those rays which, before king the mirror, were travelling *close* to the principal axis. s the 'principal focus' of which we spoke in the last graph.

ou must often have seen a caustic curve on the surface cup of tea, the circle of the cup in this case serving as mirror.

ocal length. Going back to Fig. 22/16, we may notice the distance from C to P is known as the *radius of ation* of the mirror, while the distance FP is its *focal h.* From what has been said it will be clear that the length is equal to half the radius of curvature.

Various methods are in use for finding the focal leng of a concave mirror. One of them depends on the fact th rays of light reaching the mirror from a very *distant* obj are practically parallel. For instance, if in Fig. 22/18 t rays *a*A, *b*B . . . *e*E have come from a point in the su 90 million miles away, it is clear that A*a*, B*b* . . . E*e* wo have to be produced 90 million miles before meeting—i to all intents and purposes they are parallel. In m practical work with mirrors and lenses, rays may be regar as parallel if they originate from points even 10 or 20 ft. aw

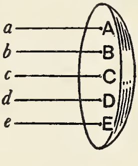


FIG. 22/18

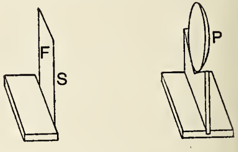


FIG. 22/19

Suppose then (Fig. 22/19), we place our mirror facing sun, and put a screen S in front of it. We move S neare the mirror or farther from it until an image of the su sharply focused on it, at F. This image is evidently the p (or rather small area) through which rays of light parallel to principal axis are being reflected—i.e. it is the principal fo By measuring the distance from F to P (the pole of the mir we have the focal length.

The screen may consist of a post-card fastened by draw pins to a block of wood. A piece of three-ply painted w is better because it is more rigid.

To mark the position of P, pass one end of a knitting-needle through a cork which is gripped by the clamp of a retort stand. Make the other end of the needle touch the pole of the mirror. The mirror may then be removed, and it is easy to measure from the screen to the end of the needle.

FIG. 22/

Instead of using the sun as our distant object, we ma the window-frames of the laboratory.

We can also use the ray-box to give us our beam of pa rays. The method (using a graining comb) has already

escribed on p. 233, when we were considering the subject f caustic curves.

The most suitable source of light is a frosted electric lamp. Vhen it is in the right position for giving parallel rays, remove ıe comb and slide a sheet of glass into the groove just in ·ont of the lens. The glass is painted white, except for a nall triangle near the centre. This triangle serves as a rightly illuminated object giving off parallel rays of light.

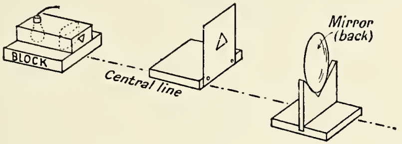


Fig. 22/21

Draw a chalk line on the bench so that the ray-box lies ntrally over it as in the figure. Place the mirror in its and slightly to one side of this chalk line, with the post-rd (mounted on its wooden block) slightly to the other side. ɔw move the card, with its block, until a sharply focused ıage of the triangle (inverted) is obtained. The distance ɔm the mirror to the image gives the focal length.

Finding the radius of curvature. The principle used in ding the radius of curvature is a very simple one. Suppose tiny source of light is placed at C, the cen-ɜ of curvature. All the rays of light from which reach the mirror strike it *normally* i.e. at right angles to that portion of the rface which they strike. They are therefore lected along the path by which they came, d so the *image* of C coincides with C itself. This suggests a means of finding the position C. We have then only to measure the tance from C to the pole of the mirror.

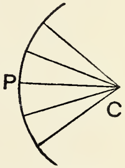


Fig. 22/22

To carry out the experiment, put a sheet of ground glass ıinted white except for a small triangle), in front of the ı-box, from which the lens has been removed. The box l be placed centrally on the chalk line, the mirror with

its stand being also arranged centrally. Now move th mirror to and fro along the line until a sharp (inverted) imag is obtained, point to point with the original triangle. Th

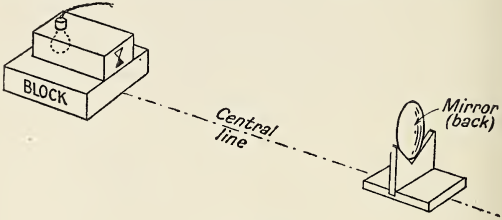


Fig. 22/23

distance from this point to the pole of the mirror gives th required radius of curvature. If we call this r, and the foc length (found in the previous experiment) is f, we ought t find, of course, that $r = 2f$.

Real and virtual images. The images so far obtained fro our concave mirrors have been *real*. They were formed b the coming together of actual rays of light, and could therefo be received on a screen. We shall now meet with anoth kind of image.

Knowing the focal length of the mirror, put it at a distan (from the front of the ray-box) slightly less than this foc length. Now try to obtain an image on a post-card. Yo

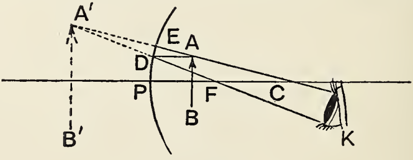


Fig. 22/24

soon find this is impossible. If, however, you stand w back from the mirror and look into it, you can see a ve clear erect image. Let us try to work out what has happene

In Fig. 22/24 P represents the pole of the mirror, C i

ntre of curvature. F, bisecting PC, is the principal focus. B, on the 'mirror' side of F, stands for the illuminated triangle. (N.B. It is usual, and convenient, to represent the uminated object by an arrow. It must not be thought at the arrow head stands for the triangle.)

From A draw a ray AD parallel to the axis CP, cutting the irror at D. This ray will be reflected through F (p. 232).

Next draw AE in the direction of CA produced—i.e. in the rection of the radius. This ray will be reflected along its n path. Clearly the reflected rays EA and DF never meet, d so cannot give rise to a real image.

But when these rays enter the eye at K, they seem to me from A′ (where they meet if produced backwards). us A is seen at A′, and similarly B is seen at B′ (for clear-ss the construction for B′ has been omitted). Hence the age of AB is seen at A′B′. Evidently rays of light are not *lly* coming from points on A′B′; they only *appear* to be doing. Hence A′B′ is known as a *virtual* image. An ential difference between the two kinds of image is that *eal image can be received on a screen, while a virtual image nnot.*

Various positions of object. We have seen that a change in position of the object causes a change in that of the image, d may also cause other changes such as erect to inverted, l to virtual, etc. Let us summarise the results so far ained.

Position of object	Position of image	Nature of image
ery far from mirror.	At F.	Real, inverted, diminished.
t C (centre of curvature).	At C.	Real, inverted, same size.
etween F and mirror.	Behind mirror.	Virtual, erect, enlarged.

ne other case remains to be explored, *viz.* when the object between F and C. It will be found in this case that the ge is on the other side of C. It is real, enlarged and erted. It is worth noting that erect images are always tual, and vice versa.

Relation between u, v and f. It seems reasonable to suppos that if an object is placed at a given distance in front of mirror of given radius of curvature, it should be possible t *calculate* the position of the image. Let us consider th problem. Suppose O is a point on the principal axis PCO of a concave mirror APB, whose centre of curvature is C. A ray of light from O strikes the mirror at E. Join CE. Then the reflected ray EO′ cuts the principal axis in O′ where $\angle O'EC = \angle OEC$. Again, a ray of light OCP, because it is travelling along a radius, will be reflected alor its own path. Thus the reflected rays EO′ and PO′ meet O′, which is therefore the image of O.

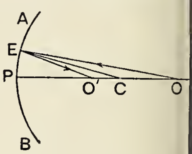


FIG. 22/25

Now because $\angle O'EC = \angle OEC$

$$\frac{CO'}{CO} = \frac{EO'}{EO} \quad \ldots \ldots \quad \text{(i)}$$

Again, if EP is small, then approximately

$$EO' = PO' \text{ and } EO = PO$$

$\therefore$ instead of (i) we may write

$$\frac{CO'}{CO} = \frac{PO'}{PO} \quad \ldots \ldots \quad \text{(ii)}$$

Suppose OP, the distance of the object from the mirr is equal to u, and O′P, the distance of the image, is v. L CP the radius of curvature $= r$.

Then $\quad CO' = CP - O'P = r - v$
and $\quad CO = OP - CP = u - r$

$\therefore$ equation (ii) becomes $\dfrac{r-v}{u-r} = \dfrac{v}{u}$.

Multiplying across, $ur - uv = uv - vr$.

$\therefore \quad ur + vr = 2uv$.

Divide throughout by uvr,

then $$\frac{1}{v} + \frac{1}{u} = \frac{2}{r} \quad \ldots \ldots \quad \text{(iii)}$$

We have seen (p. 233) that if f is the focal length, th $r = 2f$.

∴ equation (iii) becomes

$$\frac{1}{v}+\frac{1}{u}=\frac{2}{2f}$$

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iv)}$$

Equation (iv) must be carefully remembered. It evidently [en]bles us to calculate the position of the image provided we [kn]ow that of the object, and either the focal length or the [rad]ius of curvature of the mirror.

[E]xample 1. An object is placed 40 cm. from a mirror whose [rad]ius of curvation is 16 cm. Find the position of the image.

[H]ere $f = \frac{1}{2}r = 8$ cm., $u = 40$ cm., $v = ?$

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$$

$$\therefore \quad \frac{1}{v}+\frac{1}{40}=\frac{1}{8}$$

$$\therefore \quad \frac{1}{v}=\frac{1}{8}-\frac{1}{40}=\frac{1}{10}$$

$$\therefore v = 10.$$

[i.]e. the image will be **10 *cm. from the mirror.***

[A]nother method of finding *f*. The equation just considered [sug]gests another method of finding f. All we have to do is [p]ut an object in front of a mirror and in some way find the [posi]tion of its image. We then measure u (distance of object) [and] v (distance of image) and calculate f.

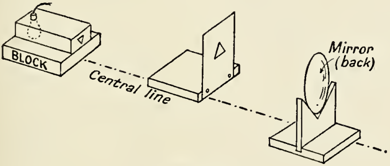


FIG. 22/26

[A]s on p. 235 we use the ray-box and a sheet of ground [glass] painted white except for a small pattern (such as a [trian]gle). This pattern will, of course, be brightly illuminated. [The] mirror is placed slightly to one side of the chalk line and [the] screen to the other, the latter being moved towards the

mirror or away from it until a sharp (inverted) image obtained. A number of results may be obtained and tabulat thus:

u	v	$\frac{1}{u}$	$\frac{1}{v}$	$\frac{1}{v}+\frac{1}{u}$	f

With careful work it will be found that the values of f ag closely, and we should take the mean. If f has been fou by one of the earlier methods (e.g. p. 234), we can eviden use the experiment just described to verify the form $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$.

Magnification. In such work as the foregoing we s notice that, generally speaking, the image and object are of the same size. The ratio

$$\frac{\textit{length of image}}{\textit{length of object}}$$ is known as the ***magnification.***

There is a very simple relation between the quantitie v and the magnification, which can be proved geometric as follows. Suppose AB is the object, DPH a concave mirror, PFCB the principal axis. AD is a ray of light parallel to the principal axis, and we have already seen that this will be reflected through the principal focus F (where F bisects PC). ACH, a ray of light passing through the centre of curvature C, will be reflected along its own path. The two reflected rays meet in A′, which is therefore the image of A. From A′ draw A′B′ perpendic to PB.

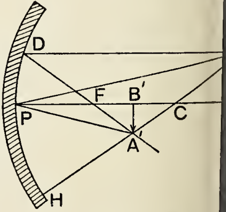


FIG. 22/27

'hen A′B′ will be the image of AB.

oin AP.

'hen because A′ is the image of A, a ray of light AP will 'eflected along PA′.

'hese rays make equal angles with the normal

$$\angle A'PB' = \angle APB.$$

. the triangles A′PB′ and APB are similar.

$$\frac{A'B'}{AB} = \frac{PB'}{PB}$$

$$\frac{\textit{length of image}}{\textit{length of object}} = \frac{\textit{distance of image}}{\textit{distance of object}},$$

we put I and O for length of image and object respectively,

nification $\frac{I}{O} = \frac{v}{u}$.

'actical applications. The things we have learnt about ave mirrors have a number of useful applications in life. Let us go back to the fact that rays of light 'lling parallel to the principal axis are reflected through principal focus. Now, by putting a source of light at F

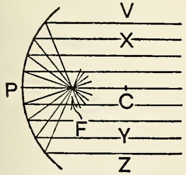


FIG. 22/28

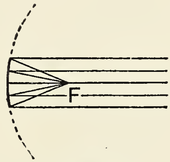


FIG. 22/29

quite easy to reverse the state of affairs. Light will then from F, strike the mirror, and be reflected parallel to rincipal axis (Fig. 22/28). Thus by putting a concave tor in a bicycle lamp or in the head-light of a motor or in a searchlight, and placing a small source of light principal focus, we can cause a parallel beam to be sent Such a beam will be effective for very long distances

because, unlike the ordinary 'divergent' beam, it is n weakened by spreading out as it travels farther from t mirror.

We saw, however, that rays parallel to the principal a are reflected through F only if they are *close* to the a Reversing the direction, it follows that only that portion the mirror which is close to the axis will serve to give u parallel beam. In short, it looks as though we can only the central portion of the concave reflector, and all the ot part would have to be cut away or blacked out (Fig. 22/29). that case most of the light from F would not be reflected at all, and our parallel beam would be greatly weakened.

The difficulty is overcome by using a reflector of the shape shown in Fig. 22/30 (a 'parabolic' reflector). It can be shown that with one of this shape, *all* rays from the principal focus are reflected parallel to the principal axis.

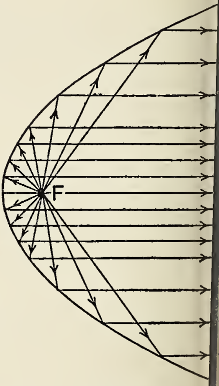


Fig. 22/30

A shaving-mirror is often made to be slightly concave (i.e. to have a large radius of curvature). A man standing between F and the mirror will then see an enlarged, erect, virtual image of his face (cf. Fig. 22/24).

A dentist also uses a concave mirror to get a view o back part of a tooth. In this case the distance from m to tooth is very small, and so the focal length of the m need only be small (again, cf. Fig. 22/24).

Convex Mirrors. We may now try to perform experim with a convex mirror similar to those done with con mirrors. We soon find, however, that we cannot obtain image on the screen, because the images are in every *virtual* (they are also erect, and diminished).

We will try, by drawing, to find the position of the i formed by a convex mirror, but first of all let us see

ppens to a ray of light travelling parallel to the principal is. As before, C is the centre of curvature and P the pole the mirror (Fig. 22/31). CP (produced to R) is the axis. 3 is a ray of light travelling parallel to RP and striking e mirror at B. Join CB and produce it to Q.

As before, the radius CB may be considered to be at right gles to the tiny bit of mirror immediately surrounding B. us CBQ is a normal to this portion of the mirror and the of light will be reflected along BG, where $\angle QBG = \angle QBA$.

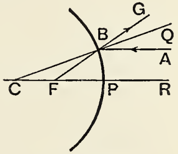


Fig. 22/31

Produce GB to meet CP at F.

By parallels, $\angle QBA = \angle BCF$.

Also $\angle QBG = \angle FBC$

rtically opposite)

3ut $\angle QBA = \angle QBG$

$\therefore$ $\angle BCF = \angle FBC$

$\therefore$ $FB = FC$.

f B is close to P, then (approximately) FB = FP.

$\therefore$ $FC = FP$.

ıs the reflected ray BG, when produced backwards, cuts axis at a point F such that F bisects PC. This result is, course, similar to what we obtained with the concave ror.

Ve should now have no difficulty in finding, by drawing,

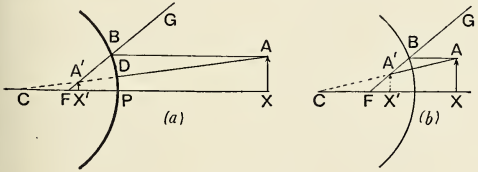


Fig. 22/32

position of an object in a convex mirror. In Fig. 22/32*a*, instance, AX is the object, and we begin by marking F, -way between C and P. The ray AB striking the mirror 3 is reflected along BG, obtained by joining FB and pro-ng to G. The ray AD, in line with the radius, is reflected

along its own path. DA and BG *appear* to come from A′ which is therefore the virtual image of A. X′, the image X, lies on the axis, vertically below A. In Fig. 22/32b t work is repeated, but with AX closer to the mirror.

Images formed by convex mirrors are *always* virtual, er and diminished.

Sign Convention. In our proof of the formula $\frac{1}{v}+\frac{1}{u}=$ we used a concave mirror, and the object was at such distance that a real image was obtained. It can be show however, that the formula applies in *all* cases—whether are dealing with a concave or convex mirror, and wheth the image is real or virtual—provided certain simple ru are observed. Various sets of rules or *conventions* are use, but in this book we shall employ what is known as t *real-is-positive* convention. According to this,

1. We measure all our distances from the pole of the mir as starting point.
2. We regard the distance as positive if it is measured t real object, image or focus, but negative if measu to a virtual image or focus.

By studying the worked examples which follow, the rea will soon learn how these simple rules are applied.

Example 2. *By a ray diagram, and also by calculation, find position and size of the image formed when an object 2 inches h is placed 3 inches in front of a convex mirror of focal length $1\frac{1}{2}$ inc*

The ray diagram is shown in Fig. 22/33, vertical measurem (e.g. length of object) being drawn half-scale as compared w horizontal. Where (as in this case) the object is not small in comparison with the other measurements, it is best to place it symmetrically across the axis, as shown.

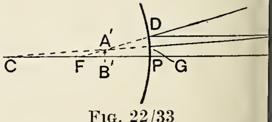


FIG. 22/33

The usual two rays from A are shown (i) AD parallel to the principal axis (reflected ray travels as though it had pas through F) and (ii) AG travelling towards centre of curvat (reflected along its own path). Thus A′ is found. It is suffici to place B′ symmetrically below the axis.

By measurement A′B′ is found to be 1 in. behind the mir and to be $\frac{2}{3}$ in. long.

By calculation. Mirror is convex, ∴ focus is *virtual*, making egative in accordance with the real-is-positive convention

∴ in formula $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$

ve have $v = ?$ $u = 3$, $f = -1\frac{1}{2}$

∴ $$\frac{1}{v}+\frac{1}{3}=\frac{1}{-1\frac{1}{2}}.$$

This gives $v = -1$, i.e. image is 1 inch from the pole of the rror and *virtual*; so it is behind the mirror.

Magnification $=\frac{v}{u}=\frac{1}{3}$

∴ length of image $= \frac{1}{3}$ of 2 in. $= \frac{2}{3}$ in.

Thus image is $\frac{2}{3}$ **in. long** and **1 in. behind the mirror.**

Note that in working out the magnification we ignore the gative sign of v. The sign only enables us to decide that image is virtual, and therefore behind the mirror.

onvex mirror as driving-mirror. The driver of a motor is required by law to fit his car with a mirror so that he y have a view of the road behind him. In practice he ays uses a *convex* mirror, because it gives him a very wide l of view. In Fig. 22/34 suppose the driver's eye is at E,

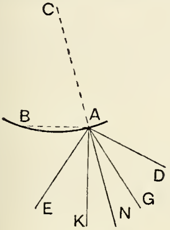


Fig. 22/34

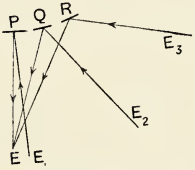


Fig. 22/35

that A is a point near the outer edge of his mirror. C is centre of curvature. Draw the normal CAN, and make AD = ∠NAE.

hus the outer edge of his mirror is reflecting rays of light, n points as far out as D. His field of view is represented roximately by the large angle EAD.

Now suppose he had used a plane mirror, represented b the dotted line AB. If we draw the normal AK, and mak $\angle KAG = \angle KAE$, we see that his field of view is represent by the much smaller angle EAG.

We can think of the convex driving-mirror in another wa We may imagine it made up of a number of very small *pla* mirrors, P, Q, R. . . .

In Fig. 22/35 the incident ray E_1P corresponding to th reflected ray PE has been drawn, and similarly the incide rays E_2Q, E_3R. Thus the first mirror enables him to s objects almost immediately behind him, while the othe enable him to see objects more and more to his off side.

A driving-mirror is mounted on an adjustable metal ar and if the motorist requires a wider field of view on the side, he pushes this arm slightly away from him.

Any car driver, by the way, will tell you that when overtaking car has nearly drawn level, its image in the drivi mirror becomes much larger. This can easily be understo by a comparison of Figs. 22/32 (*a*) and (*b*) on p. 243. In the object is much closer to the mirror than in (*a*), and see that the image is much larger.

Similarly, when looking into a convex mirror you ha doubtless been impressed with the noble proportions of yo own nose. The explanation, of course, is the same as th just given. Your nose is nearer to the mirror than is the r of your face, and so forms a relatively larger image.

We will conclude this chapter by working one or two m typical examples.

Example 3. *An electric-lamp bulb is placed with its very sm filament on the principal axis of a concave mirror, and* 4 *cm. front of it. The reflected light appears to diverge from a p which is* 12 *cm. behind the mirror. What is the radius of curvat of the mirror?* J.M.B.*

The image is virtual, and 12 cm. from the mirror.

Thus in the formula $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$ we have

$v = -12$ cm., $u = 4$ cm., and $f = ?$

$$\therefore \quad \frac{1}{-12} + \frac{1}{4} = \frac{1}{f}$$

This gives $f = 6$ cm. and the radius of curvature $= 2f = 12$

Example 4. Find the distance fron the face at which a concave *wing mirror must be held to give an image magnified two-fold,* *he radius of curvature of the mirror is* 4 *ft.* O.C.*

Iere the image is obviously erect. It must therefore be iind the mirror, and virtual, i.e. v is negative.

Vow $$\frac{I}{O} = \frac{v}{u}, \text{ and } \frac{I}{O} = 2$$

$$\therefore \quad \frac{v}{u} = 2 \text{ (numerically)}$$

3ut v is negative, $\therefore \quad v = -2u$

Also $$r = 4 \text{ ft.}$$

$$\therefore \quad f = 2 \text{ ft.}$$

f required distance from face $= u$ ft.

Then $$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

$$\frac{1}{-2u} + \frac{1}{u} = \frac{1}{2}$$

giving $u =$ **1 ft.**

xample 5. Taking the diameter of the sun to be 870,000 *miles,* *the distance of the sun from the earth* 93,000,000 *miles, find the* *neter of the image of the sun produced by a concave mirror of* *us of curvature* 100 *ft.* O.C.*

nce the object is very distant, the image will be formed at principal focus, which is 50 ft. (half the radius of curvature) ont of the mirror.

$$\therefore \quad v = 50 \text{ ft.} = \frac{50}{5280} \text{ miles.}$$

et required diam. $=$ I miles.

ien magnification $= \frac{I}{O} = \frac{v}{u}$

$$\therefore \quad \frac{I}{870{,}000} = \frac{\frac{50}{5280}}{93{,}000{,}000} = \frac{50}{5280 \times 93{,}000{,}000}$$

$$I = \frac{50 \times 870{,}000}{5280 \times 93{,}000{,}000} \text{ miles}$$

$$= \frac{50 \times 870{,}000}{5280 \times 93{,}000{,}000} \times 5280 \text{ ft.}$$

$$= 0{\cdot}47 \text{ ft.} = \mathbf{5{\cdot}6 \text{ in.}}$$

Questions

A

1. How are shadows formed? Draw a diagram to show t kind of shadow you would expect to find on a screen when a la spherical source of light casts a shadow of a small ball upon What fact do you make use of in your drawing, and how would y verify it experimentally? *Dur.*

2. State the laws of reflection of light, and describe an exp ment by which you could prove *one* of them.

3. Make a labelled diagram of a concave mirror showing t *centre of curvature*, the *principal focus* and the *principal ax* Also show the *pole* of the mirror.

4. Use diagrams to illustrate the formation of *real, virtu erect* and *inverted* images by means of concave and conv mirrors. *O.C.*

5. What is meant by the terms *radius of curvature, focal len virtual image* ?

A convex mirror has a radius of curvature of 20 cm. Dra diagram to scale to show the paths of rays of light from an obj which gives rise to an image of half the size. What is the dista of the object from the mirror? A graphical solution of t problem would be preferred. *Dur.*

6. A luminous object is placed 6 in. from (*a*) a plane mir (*b*) a concave mirror of focal length 9 in. In each case dra ray diagram to illustrate the formation of the image, and g details of the nature, position, and magnification of the ima *C.W.B.*

7. By means of a ray diagram, explain the working of a mo car driving-mirror.

B

1. Describe the formation of an image by a pin-hole came Explain what happens to the image when (*a*) the hole is gradu enlarged, (*b*) the screen is moved away from the pin-hole, (*c*) shape of the hole is altered.

What fundamental principle of optics is illustrated by th experiments? *Camb.*

2. If the length of a pin-hole camera from hole to plat 2 in., and a 6-ft. man stood 9 ft. from the hole, what would the size of his picture? *J.M.B.**

3. Explain briefly, using diagrams, how an eclipse of the takes place, distinguishing between total and partial ecli What law of light do you assume in your explanation? *Ca*

4. Describe an experiment by which you could show tha a small object is placed in front of a plane mirror, its image i far behind the mirror as the object itself is in front of it.

5. Assuming the laws of reflection of light, give a geometrical oof of the statement in question 4.

6. Describe an accurate experiment to find the focal length of oncave mirror.

An object, 3 cm. high, is placed 15 cm. from the pole of a icave mirror of 10 cm. radius of curvature. Find the position the image by a graphical construction, which should be done full scale. Explain each step in the construction. State also size and nature of the image. *Oxf.*

. Find the position and size of the image of an object 4 cm. h placed 100 cm. in front of a concave mirror of focal length cm. *Camb.**

. An object is 10 in. from the centre of curvature and 20 in. n the principal focus of a concave mirror. What is the ition and magnification of the image? What changes in the ge occur when the object is moved a distance of 25 in. towards mirror? *Dur.*

. By means of a ray diagram, explain the use of a spherical cave mirror to give an erect image, magnified twice.

0. A man using a *concave* shaving mirror sees an erect image his face enlarged one and a half times when his face is 10 in. n the mirror. Draw a diagram to scale to illustrate the nation of the image, and from it deduce the distance of the ge from the mirror and the radius of curvature of the mirror. *Dur.**

1. Describe the optical arrangement in a searchlight giving arallel beam, and explain the adjustment necessary to give verging beam.

y day, searchlights should never be left in such a way that might point at the sun; explain this fact. *J.M.B.**

2. How would you verify the formula relating the distance n object and its image from the pole of the mirror?

3. The following points, plotted on squared paper, will give rabola with its focus F at $x = 0{\cdot}5$.

x	0	0·1	0·2	0·5	1·0	1·5	2·0
y	0	0·45	0·63	1·0	1·41	1·73	2·0

raw the parabola. Regarding F as a point source of light, any ray to meet the curve at A_1, and from A_1 draw a line $_1$ parallel to the axis. This should be the reflected ray esponding to the incident ray FA_1. To test this, draw a ent to the curve at A_1 (by eye, using your ruler), and then the normal at A_1. Measure the angles of incidence and ction.

epeat with several other points, A_2, A_3, etc.

CHAPTER 23

PHOTOMETRY

In the preceding chapter there was a reference to the measu ment of the velocity of light. In the present one we shall c sider some much more 'every-day' measurements. If a m were buying a source of light (e.g. an electric light bulb) would not bother about the speed at which light from the bu travels into space, but he would certainly want to know h much light it throws out—i.e. its *illuminating power*.

Again, a man in a reading-room may complain to t attendant that the lighting is poor, and the attendant m reply that the lights in use are actually very powerful. B reader and attendant may be right. The powerful lights m be at too great a distance from the periodicals, etc. We that what is wrong is not the illuminating power, but *intensity of illumination*. We must evidently distingu clearly between the two. Illuminating power is a quant that depends only on the source of light, while intensity illumination depends not only on the strength of the sou of light, but also on its position. The distinction will beco clearer as we proceed.

The Standard Candle. Brightness. To measure illuminat power we evidently need some unit, and the one chosen is *standard candle*. This was defined by an Act of Parliam passed in 1860 as *a candle made of sperm wax, weighing sixth of a pound, and burning away at the rate of* 120 *gra per hour*.

Of course the important point about a unit is that it sho be *constant*, and it was thought that by defining the mater the rate of burning, etc., a really constant illuminating po would be secured. Actually the standard candle is no very satisfactory unit, for its illuminating power va slightly according to the shape of the wick, the pressure humidity of the air and other circumstances. Vernon H court found that much more constant results could be obtai by burning pentane vapour under certain specified conditi (pentane is a light oil obtained from paraffin). The 'Haro

ntane lamp' has an illuminating power equal to that of standard candles, and is now always used as the official ndard.

The candle-power of a few well-known sources of light y be mentioned. A 50-watt lamp has usually a candle-ver of about 40; a good incandescent gas mantle about 96. ectric torches naturally vary a great deal, but a very nmon type (3·5 volts, 0·3 amps) is from 1 to 2 c.p.

Ve must not confuse candle-power with *brightness*. Suppose incandescent gas mantle and an acetylene flame are of ial candle-power (as might quite well be the case) but the ntle has a surface area of 10 sq. in. and the acetylene flame only 1 sq. in. The acetylene flame would be much more zling to look at than the mantle. That is because the ount of light given off *per square inch of surface* is ten es as great.

t is worth noticing that it is this factor—light given off *unit area*—which determines brightness. That is why modern electric-lamp filament is so often enclosed in nslucent instead of transparent glass. Owing to the ness of the filament, the light is given off from a very ll area, and the filament would be too dazzling for comfort. earlier lamps were of clear glass. They did not (necessarily) off less light, but the light was given off from a stouter nent, which was therefore less brilliant than the modern with its smaller surface area.

ntensity of Illumination. Let us now look more closely the question of intensity of illumination, which, as we e seen, depends both on the candle-power of the light lights) concerned and on its distance from the surface we considering. A fairly obvious unit is the **foot-candle,** ch we define as *the intensity of illumination of a surface ed one foot from a standard candle, and in such a direction the light strikes it at right angles.* The last half of the nition is often overlooked, but it is important, because intensity with which a surface is illuminated depends much on the direction at which the light strikes it. point will be taken up again in Example 3 (p. 260).

or comfortable reading we need an intensity of illumination t least 1 ft.-candle, and a woman sewing with dark material

would need 6 or 7. A watchmaker would need still more- 10 or 12. The lighting of a classroom would be consider poor if the intensity of illumination were less than 3 ft candles. We shall see presently how these intensities c be measured, but we cannot attack this problem until w have obtained an answer to a question which we may expre thus: *How much* does the intensity of illumination of surface fall off as we increase its distance from the source light?

For instance, light from a standard candle is falling up a surface 1 ft. away. The intensity of illumination obviously 1 ft.-candle. What would this intensity be if w increased the distance to 2 ft. or to 3 ft.? (It is understo that the light falls 'normally' upon the surface in all cases.)

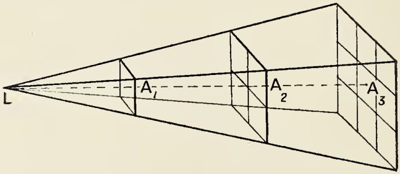


FIG. 23/1

Suppose a small source of light L is throwing out a beam square cross-section. (If L is contained in a glass enclosu this is easily secured in practice by pasting black paper o the container, and then cutting out a small square.) Supp the square A_2 is twice as far from L as is the square Because the distance is twice as great, it follows from simi triangles that a *side* of the square A_2 is twice as long a *side* of the square A_1. Therefore the *area* of A_2 is four ti the *area* of A_1. As the same amount of light reaches A_2 A_1, but has to cover four times the area, it follows that intensity of illumination of A_2 is only a quarter that of A_1.

Similarly, if the square A_3 is three times as far away as the intensity of illumination of A_3 will be only one-ni that of A_1 and so on.

The conclusion thus reached is known as the ***Law Inverse Squares,*** and may be stated as follows: *The inten*

illumination of a surface varies inversely as the square of distance from the source of light.

Thus, while the intensity of illumination due to a standard candle at a distance of 1 ft. is 1 ft.-candle (by definition), 2 ft. the intensity is only $\frac{1}{4}$ ft.-candle, at 3 ft. 1/9 ft.-candle so on. If we use two candles, the intensities (in foot-candles) would be respectively 2, 2/4 ($= \frac{1}{2}$) and 2/9. In general, if $c =$ illuminating power measured in candles, intensity of illumination (in foot-candles) and $d =$ ance (in feet), then $i = \frac{c}{d^2}$. Thus we have a simple numerical tionship connecting illuminating power, distance and nsity of illumination.

With the law of Inverse Squares in mind, we might think t in an ordinary room the intensity of illumination at) 12 ft. from the electric-light bulb would be only one-h of the intensity at 4 ft. (distances are as 3 : 1, therefore nsities are as $1 : 3^2$). This is by no means the case, ause the walls of the room reflect the light. Thus every it in the room receives light, not only from the bulb, but n the walls, and the illumination may be fairly even oughout.

y this time the reader will have acquired fairly accurate s of the terms Illuminating Power and Intensity of mination, and it will be well to express them in formal nitions.

he ***illuminating power*** of a source of light means *the rate hich energy in the form of light is being emitted by that source.* n practice, it is measured in standard candles.

he ***intensity of illumination at a point***, means *the rate hich energy in the form of light is being received per unit rea immediately surrounding the point, such area being posed to be at right angles to the direction of the light.*

is measured in foot-candles. Another unit is the metre-lle or *lux*.

omparison of Illuminating Powers. We are now in a tion to compare the illuminating powers of two sources ght, say a small electric bulb and a gas flame.

n a sheet of drawing-paper to the bottom of a drawer, thus ing a screen (Fig. 23/2). Place a retort stand so that the

vertical rod is 2 or 3 in. in front of the screen, and place the ga flame G (a fish-tail burner) so as to throw a shadow S_g. No place the electric bulb B so that the shadow it makes, S_b, almost touching S_g.

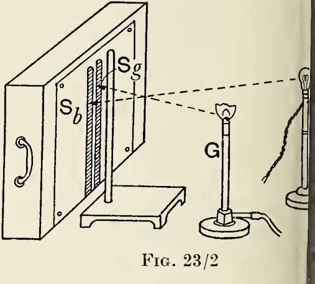


FIG. 23/2

Clearly the shadow S_b is illuminated by the gas-flame, while S_g is illuminated by the bulb. Move the gas-flame (or bulb) towards or away from the screen until the shadows are of equal depth, and then measure the distance of each source of light from the shadow it is illuminating. Suppose this distance is 24·0 in. for the gas-flame (candle-power c_g) and 36·0 in. for the bulb (candle-power c_b). Then the intensities of illumination may be express as $\frac{c_g}{24^2}$[1] and $\frac{c_b}{36^2}$ respectively. But we have arranged that th intensities shall be equal. Hence we have $\frac{c_g}{24^2} = \frac{c_b}{36^2}$, from wh we easily work out that $c_g : c_b = 1 : 2\frac{1}{4}$.

A similar experiment is sometimes carried out to illustr the law of Inverse Squares. Five similar candles are tak and four of them, placed close together, are used as a sin source of light, to be compared with the light from the rema ing candle. When the shadows are of equal intensity, it found that the '4-candle' light is at *twice* the distance of '1-candle' light. Calling these distances $2d$ and d, we hav

Intensity of illumination from 4 candles at distance $2d$
= Intensity of illumination from 1 candle at distance d.
∴ Intensity of illumination from 1 candle at distance $2d$
= 1/4th intensity of illumination from 1 candle at distanc

Thus as the distance is doubled the intensity of illuminat is reduced to one-quarter, as required by the law of Inv Squares. Other results may be obtained by varying number of candles. Actually the experiment is not a v

[1] 24 in. = 2 ft., so that the intensity in foot-candles would $\frac{c_g}{2^2}$. $\frac{c_g}{24^2}$ really gives the intensity in inch-candles, but there is objection so long as we do the same for both sources of light.

isfactory one, partly because when candles are burning se together the wax melts at an abnormal rate, and each ndle gives more than its ordinary amount of light.

An instrument used for measuring candle-power (or com-ing candle-powers) is known as a ***photometer,*** the process lf being known as photometry (cf. calorimeter and calori-try). The very simple instrument we have so far used is ed *Rumford's shadow photometer.* The inventor, Rumford, he same man we have met with already in connection h the overthrow of the caloric theory of heat.

unsen's Grease-Spot Photometer. Another very simple effective photometer depends on the use of a grease-spot, was invented by the famous Bunsen.

et a drop of fat or oil fall on a piece of paper, and hold latter up to the window. The grease-spot is lighter than rest of the paper. Hold it away from the window. It appears dark. Clearly, when we view the grease-spot n the side of greater illumination it appears darker than rest of the paper, and when we view it from the side of er illumination it appears lighter. It is reasonable to pose that *when the illumination is equal on the two sides, grease spot will appear neither lighter nor darker than the of the paper*—i.e. the grease-spot as such will cease to be ble.

e can easily test this conclusion by putting our grease-ted paper in a simple wire frame, darkening the room, then putting lighted candles on opposite sides of the er, but at equal distances, so that the illumination shall he same on both sides. The grease-spot is invisible, but ediately comes into view if we disturb the balance by ing the position of one of the candles.

is not very hard to understand the appearance of the se-spot. It is more translucent than untreated paper—t allows light to pass through it more readily. Suppose re viewing it from the side on which more light is falling. use it is transmitting *more* light than the rest of the r, it is reflecting *less*, and so it appears darker. If, ever, the illumination is the same on both sides, the se-spot, though still *reflecting* less light than the rest of paper, makes up the deficiency by the extra light it is

now *transmitting* from the other side. The result is that observer now receives exactly as much light from the grea spot as from the rest of the paper, and so he cannot distingu one part from the other.

Determination of Candle-power. Suppose we wish to the photometer to compare the candle-powers of two sour of light, say the electric bulb and fish-tail burner alre used with the shadow photometer.

Put the bulb on one side and the fish-tail burner on the ot and adjust the distances so as to make the spot disappear. two mirrors are so placed that both sides of the screen can be viewed at the same time —a considerable improvement.

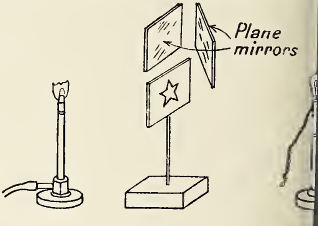


FIG. 23/3

Suppose the distance of the bulb is found to be 30 in. and that of the burner 20 in. Let c_b = candle-power of bulb and c_g = candle-power of burner. Then intensity of illumination due to bulb $= \frac{c_b}{30^2}$ and intensity of illumination due to gas-bu r $= \frac{c_g}{20^2}$ (cf. foot-note p. 254).

But the intensity is the same for each side.

$$\therefore \qquad \frac{c_b}{30^2} = \frac{c_g}{20^2}$$

$$\therefore \qquad \frac{c_b}{c_g} = \frac{30^2}{20^2} = \frac{900}{400} = 2\tfrac{1}{4} : 1.$$

No matter what kind of photometer has been use n making the above comparison, if the candle-power of o the sources of light is known, we can easily calculate th the other. Thus in the case just considered, suppose bulb is known to be of $4\frac{1}{2}$ c.p. For $\frac{c_b}{c_g} = \frac{2\frac{1}{4}}{1}$ we write $\frac{4\frac{1}{2}}{c_g}$ $\frac{1}{4}$ 1 whence $c_g = 2$ c.p.

To secure good results with the grease-spot photom certain precautions have to be taken.

There must be no sources of light other than the two l g

npared—i.e. the room must be darkened. It is desirable
to have darkened walls, for otherwise, by reflecting, they
ve as sources of light.

Jnglazed paper* should be used for a screen. Owing to power of reflection, glazed paper is very likely to be brighter some parts than others, and this would affect the degree visibility of the grease-spot.

Keeping one of the sources of light, and also the photo-er, fixed in position, *four* readings of the distance of the er source of light should be obtained and the average of four taken as the true reading.

i) grease-spot invisible as viewed from one side;
ii) the same, but viewed from the other side;
i) and (iv)—the same as (i) and (ii), but with the photometer made to face in the opposite direction.

ne experiment should be repeated several times with the ces of light at various distances from the photometer, results being worked out and the average taken as the answer.

experiments with the shadow photometer—

) The room need not be specially darkened, because stray light will affect both shadows to the same extent.
) Unglazed paper should be used.
) The question of reversing the photometer, etc., obviously does not arise.
Repetition of the experiment, with the sources of light at various distances is, of course, desirable.

e shadow photometer is now of little more than historical est. Bunsen's instrument is better, but many photors have been devised which are superior to either of them. of them—not at all hard to make—is the *Conroy Photo-*. The instrument is shown in plan (with the lid re-d) in Fig. 23/4. It consists of a small box in which openings have been made, one for observation, the two to admit light from the two sources to be compared. light falls on screens of *unglazed* cardboard, and must them at the same angle. In practice about 58° is l to be suitable.

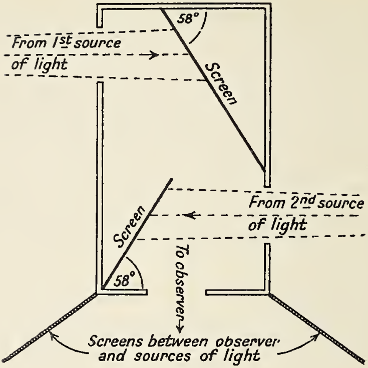
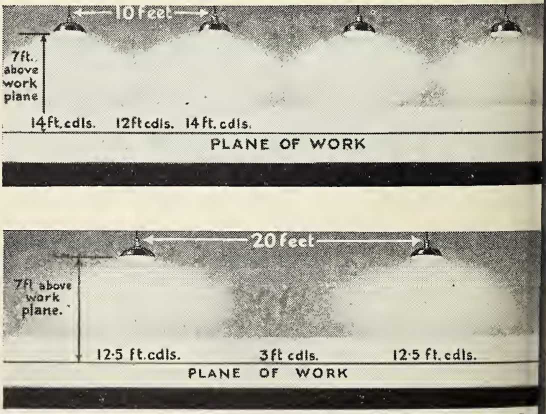


Fig. 23/4

On making a first observation it will probably be fo
that the edge of the front screen is easily seen against
other one as a background. This means that the two



By courtesy of Lighting Service Bur

What the Photometer Reveals

t equally illuminated, and the distances of the sources of ht are adjusted until the edge of the front screen is practically visible. The distances from the two sources of light to s edge are then measured, and the results are worked out the principle already explained.

[t is often necessary to measure the intensity of illumination lifferent parts of a room, and for this a *light-meter* is employed. e essential part of this instrument is photoelectric cell, which depends on principle that an electric current y be produced by the action of light a specially prepared surface, the insity of the current being proportion- to the intensity of illumination. A dle moves over a scale graduated to w foot-candles as in Fig. 23/5.

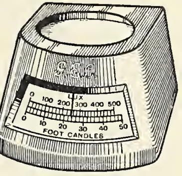


FIG. 23/5

By courtesy of General Electric Co. Ltd.

'he illustration on p. 258 suggests a light-meter may be used to compe the efficiencies of two different systems of lighting.

Ve may conclude this chapter with one or two calculations.

xample 1. *A man can just read a newspaper when he stands at stance of 20 ft. from a 100-candle-power lamp. At what distance d he just read it using a single candle?*

ntensity of illumination $= \frac{100}{20^2}$ in the first case and $\frac{1}{x^2}$ in the nd, where x is the required distance in feet. These intensities equal, being in each case the minimum required for reading.

$$\therefore \quad \frac{100}{20^2} = \frac{1}{x^2}$$

$$\therefore \quad 100x^2 = 400$$

$$\therefore \quad x = \mathbf{2\ ft.}$$

xample 2. *Two lamps of equal candle-power are placed 8 ft. t, with a grease-spot photometer midway between them. A ked-glass screen is now placed against one of the lamps, and it is d that it has to be moved 1 ft. nearer the photometer to make the se-spot invisible once more. What percentage of the light is ff by the smoked screen?*

S

Suppose the candle-power of each lamp $= c$, and that x% the light of one of them is cut off by the screen. Its can power may now be regarded as $\frac{100 - x}{100} \times c$, and its dist from the screen has been reduced to 3 ft.

$$\therefore \quad \text{intensity of illumination} = \frac{\frac{(100 - x)c}{100}}{3^2}$$

$$= \frac{(100 - x)c}{900} \text{ ft.-candles.}$$

The unscreened lamp (c candle-power at a distance of 4 gives an intensity of $\frac{c}{4^2} = \frac{c}{16}$ ft.-candles.

The two intensities are equal.

$$\therefore \quad \frac{(100 - x)c}{900} = \frac{c}{16}$$

Cancelling c, we have $\frac{100 - x}{900} = \frac{1}{16}$

$$\therefore \quad 1600 - 16x = 900$$

which gives $x = 43\frac{3}{4}$.

Thus the percentage of light cut off is **$43\frac{3}{4}$**.

Questions

1. What do you understand by the inverse square law applied to optical illumination? How is it applied in laboratory to compare the illuminating powers of lamps?

A satisfactory photographic print on gas-light paper is obt when the printing-frame, held at a distance of 2 ft. from a s electric lamp, is exposed to the light for 5 sec. At what dist from the lamp must the frame be held in order that an expo of 20 sec. shall produce the same result? *O.C.*

2. Describe a simple photometer and show how to use it to pare the candle-powers of two similar lamps. Why is it esse to conduct photometric experiments in a darkened room?

Calculate the intensity of illumination at a point on a s screen 2 ft. away from a small 10 candle-power lamp and pendicular to the incident light. What will the intensit illumination on the screen be if a plane mirror is placed behind the lamp and parallel to the screen, assuming that mirror reflects 100% of the light incident upon it? *O.C.*

3. Explain carefully the meaning of *intensity of illumin at a point on a surface.*

A small 20-candle-power lamp is placed 4 ft. above the c of a circular table which it illuminates. Would the tabl uniformly illuminated? Give reasons.

Find (1) the intensity of illumination at the table centre

v far above the centre the lamp should be placed to produce intensity of illumination there twice as great as it was ginally? *Dur.*

. The candle-powers of two sources of light are in the ratio 1 : 1. If they are placed 200 cm. apart, where should a screen placed so that the intensities of illumination on both sides equal? *O.C.**

. An electric lamp is 6 ft. from a screen. A glass plate which s off 19% of the light is interposed between the lamp and en. How much must the lamp be moved in order to restore intensity of illumination on the screen to its original value? *Lond.**

A bright light gives an illumination of 2 ft.-candles 40 yd. y. Calculate the illumination at 20 yd. distance if a sheet aper which absorbs half the light incident on it is placed in t of the lamp. *J.M.B.**

Define a *foot-candle*. A 40-candle-power lamp is placed . away from another lamp L, and a screen placed between n at 5 ft. from the 40-candle-power lamp is found to be equally ninated on both sides. If the 40-candle-power lamp is aced by one of twice its power, the screen being kept in the e place, where must the lamp L be placed if the screen is still e equally illuminated on both sides? *C.W.B.*

CHAPTER 24

REFRACTION AT PLANE SURFACES

NOT many pages back we were considering a very import fact about light—that it travels in straight lines. In present chapter we shall be discussing the fact that it does n at least not always!

The contradiction, of course, is only apparent. A ray light maintains its straight-line direction so long as it c tinues to travel *in the same medium.* If it enters anot medium it changes its direction, the phenomenon being kn as *refraction.* We have a very familiar illustration in the fact that a straight stick with its end dipping in water appears to be bent at the point where it enters the water (Fig. 24/1).

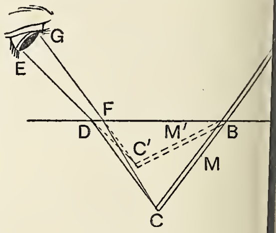


FIG. 24/1

As we saw in our earlier book, this is because a ray of light passing through a certain medium (in this case water) changes its direction on entering another medium (in this case air), this chang of direction being known as *refraction.*

Suppose ABC is the true position of the stick, the en C being in water. Consider a ray of light CD travelling f m water to air. It is refracted at D, follows the changed d c- tion DE, and enters the eye at E. Similarly another ra F follows the path FG and enters the eye at G.

Produce ED and GF to meet at C′. Now, *to the eye* rays DE and FG seem to come from C′, and so the poi C seems to be at C′. B, where the stick cuts the surface, ill be seen in its true position, while points between C a B (e.g. M) will be seen in positions between C′ and B (e.g. ′). Thus BC will be seen in the position BC′, and the subm ed part of the stick will appear 'bent.'

Other facts can be explained in a similar way. us

ig. 24/2*a* shows an observer's eye so placed that he cannot ɘe the brass plug at the bottom of a wash-bowl. In Fig. ɬ/2*b* the plug has come into view, though his eye is still in ıe same position.

In Fig. 24/3, C is (say) a pebble at the bottom of a pond. wing to refraction, rays of light from C appear to come from

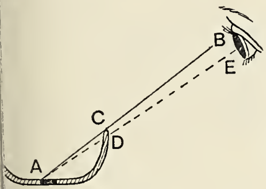


Fig. 24/2*a*

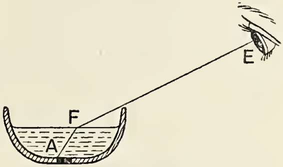


Fig. 24/2*b*

nearer the surface—i.e. the pond appears to be shallower ın it really is.

N.B. It will be seen later that KC′ is about three-quarters KC, and this suggests the best way to draw a good diagram. er marking C, put in C′ at three-quarters the depth. Draw ıight lines C′DE and C′FG (to reach the eye at E and G), ting the surface at D and F. Then join CD, CF. (In the ıre on the right, the effect is exaggerated for the sake of ırness. The figure on the left is more accurate.)

n the experiments so discussed, we cannot ually *see* the rays of ıt changing direction as y pass from water to as shown in Figs. 1–3. It is quite easy, vever, to make this nge of direction visible. h the help of a cylinal lens, the ray-box is le to give a parallel rgent beam. Into the ɔve at the front of the we slide a piece of

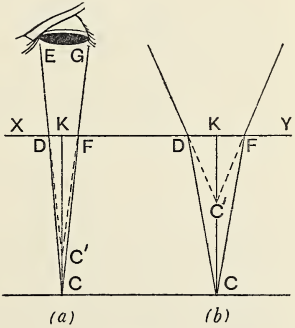


Fig. 24/3

blackened cardboard, with a hole of about $\frac{1}{4}$-in. diameter the middle of it. The beam strikes a mirror tilted as sho in Fig. 24/4. This throws it obliquely downwards, and strikes the upper surface of water in a trough suitably su ported. The path of the beam through the water is made visible by the addition of a little eosin, and to follow its path through the air we make the latter smoky with the help of smouldering brown paper.

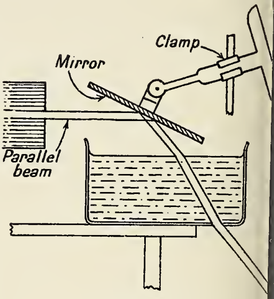


FIG. 24/4

After leaving the mirror, the beam is observed to change its direction on entering the water and again on leaving it. The directions before entering and after leaving appear to be parallel.

Measurement. Although in the preceding two or th pages we have repeatedly noted the *fact* of refraction, have so far made no attempt at *measurement*. We can ma some progress with the apparatus just mentioned. By tilt

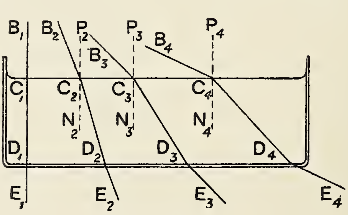


FIG. 24/5

the mirror at different angles we can vary the angle of incide Thus (Fig. 24/5) the incident ray B_1C_1 is travelling along normal—i.e. the angle of incidence is 0°. In the next exp ment the angle of incidence is increased to $B_2C_2P_2$, afterwards to $B_3C_3P_3$ and $B_4C_4P_4$.

As we increase the angle of incidence it is soon very obv

it we are also increasing the angle of refraction (i.e. the gle between the refracted ray and the normal). The angle C_3D_3, for instance, is greater than $N_2C_2D_2$, and $N_4C_4D_4$ than C_3D_3. It is clear then that *the greater the angle of incidence, greater the angle of refraction.*

At once the further question arises: Is the angle of refrac- n *proportional* to the angle of incidence? For instance, if double the angle of incidence, shall we find that the angle efraction is also doubled?

Clearly we need to be able to measure our angles, and with apparatus of Fig. 24/4 we cannot do this with any degree accuracy. Something can be done on the lines indicated Fig. 24/6. A slab of plate glass 'frosted' on one of its

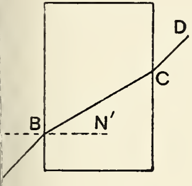


Fig. 24/6

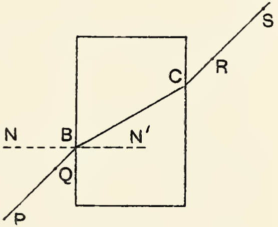


Fig. 24/7

angular faces is laid rough side downwards on a sheet of er. AB is a very narrow beam of light from a ray box h strikes the slab at B, and we can easily trace its path through the glass. The angle of incidence ABN and the e of refraction CBN′ can be measured with some degree ccuracy. We can then vary the angle ABN, producing esponding changes in the other angle, CBN′, and we can try to find if there is any definite connection between wo.

ore accurate results can be obtained by the use of pins.

e slab (which need not be frosted) is laid down on a sheet per as before, and two pins P, Q, are placed upright on the r (Fig. 24/7). Two other pins R and S are now so placed on ther side of the block, that as we look *through* the glass (not the top), P, Q, R and S all seem to be in a straight line.

This indicates that a ray of light which entered the glass in direction PQ has emerged in the direction RS. With a sh pencil, we draw the outline of the block and mark the positi of the pins. Block and pins may then be removed. We j PQ and produce to meet the trace of the block at B. Similar we obtain C by producing SR. BC now marks the path of ray through the block.

We draw the normal NBN′ and measure the angle of incide NBP and the angle of refraction N′BC.

We now repeat the experiment, setting P, Q, at a differ angle to the normal and obtaining a new value for the angle refraction N′BC; and so on until we have got a set of val something like this:—

Angle of incidence NBP . .	0° *	10°	20°	30°	40°	50°	60°	7(
Angle of refraction N′BC . .	0°	$6\frac{1}{2}$°	13°	$19\frac{1}{2}$°	$25\frac{1}{2}$°	31°	35°	3(

* Notice that a ray travelling *normally* passes into the second med without deviation.

The above results are about as nearly correct as one co expect to obtain, using an ordinary protractor. In none them does the error exceed $\frac{1}{4}$°. Can we see any obvi connection between the angles of incidence and the an of refraction? As the angle of incidence doubles, from 10 20°, the angle of refraction doubles from $6\frac{1}{2}$° to 13°. A trebles, 10° to 30°, the angle of refraction also trebles, $6\frac{1}{2}$ $19\frac{1}{2}$°. It looks as if we are on the track of a very simple But when the angle of incidence goes up four-fold, 10 40°, the angle of refraction goes up from $6\frac{1}{2}$° only to (though $6\frac{1}{2} \times 4$ would be 26). We are just a little uneas

If our 'very simple law' holds good, the numbers u 50°, 60° and 70° should be $6\frac{1}{2} \times 5 = 32\frac{1}{2}$, $6\frac{1}{2} \times 6 = 39$ $6\frac{1}{2} \times 7 = 45\frac{1}{2}$ respectively. Instead, they are only 31, and 39. The law is evidently not quite so simple as it loo at first sight. We might say, perhaps, 'As the angl incidence increases, the angle of refraction increases in same ratio; but this statement is true only for *small* an of incidence, up to 30° or 40°.'

This is not very satisfactory, but it seems to be the we can do.

And indeed it was the best that *anybody* succeeded in d

ɔr many centuries until 1621, when Snell, a young professor f mechanics at Leyden, hit upon the true law. Let us re-rite the above results, making provision for entering the *nes* of the angles as well as the angles themselves.

Angle of incidence (i)	0°	10°	20°	30°	40°	50°	60°	70°
Angle of refraction (r)	0°	6½°	13°	19½°	25½°	31°	35°	39°
Sin i . .	0	0·174	0·342	0·500	0·643	0·766	0·866	0·940
Sin r . .	0	0·113	0·225	0·334	0·430	0·515	0·574	0·629
$\frac{\text{Sin } i}{\text{Sin } r}$ . .		1·54	1·52	1·50	1·50	1·49	1·51	1·49

Making allowance for errors of experiment (remember ır measurements were made only to the nearest half-degree), e law stands out pretty clearly. The *sine* of the angle of cidence is in a constant ratio to the *sine* of the angle of fraction. A more exact statement of the law will be made ortly.

Going back to our experiment with the narrow beam ig. 24/6) we notice that the refracted ray lies *in* the plane the paper—i.e. in the plane containing the incident ray 3 and the normal BN. We get the same result, though a tle less obviously, from the experiment with the pins. ɛre, instead of the narrow beam travelling visibly in the ıne of the paper, we have only to remember that it travels m the *hole* made by P to the holes made by Q, R, S, all of ich, of course, lie in the plane of the paper. Our laws of raction may now be formally stated.

1. *The refracted ray lies in the plane containing the incident and the normal, and on the opposite side of the normal.*

2. *For a given pair of media, the sine of the angle of incidence rs a constant ratio to the sine of the angle of refraction.*

N.B. If the two media are denoted by A and B, this con-nt ratio is known as the *index of refraction from A to B*, l is expressed as ${}_A\mu_B$ or μ_{AB} (μ is a Greek letter pronounced ı'). If the first medium A is air,[1] the constant ratio is n known as the *refractive index of B*.

[1] Strictly speaking, we should say, 'if A is a *vacuum*'; but the ɛrence is so slight that for ordinary purposes we may ignore it.

In the table on p. 267, for instance, $\sin i \div \sin r$ (comin to about 1·50) gives the refractive index of glass.

Direction of refracted ray. If we know any two of the thr quantities i (angle of incidence), r (angle of refraction) and (index of refraction), we can evidently use the relationshi $\mu = \sin i \div \sin r$ to find the third. If for instance $i = 3$ and $r = 19\frac{1}{2}°$, then $\mu = \frac{\sin 30°}{\sin 19\frac{1}{2}°} = \frac{0·500}{0·334} = 1·50$.

Example 1. *A narrow beam of light passes from air into wate the angle of incidence being 60°. Find the angle of refraction giv that the index of refraction of water is 1·33.*

We have $i = 60°$ and $\frac{\sin i}{\sin r} = \mu$

$$\therefore \quad \frac{\sin 60°}{\sin r} = 1·33.$$

$$\therefore \quad \sin r = \frac{\sin 60°}{1·33} = \frac{0·866}{1·33} = 0·651.$$

Referring to a table of sines, we find that $r = \mathbf{41}°$ (approx.)

The answer may also be obtained by a simple geometric construction, thus:—

Let the two media be separated (in section) by the straight line AB. From O draw the normal NON′.

Draw OC making $\angle$NOC = 60°, so that CO now represents the incident ray. From OA cut off OD = 1 unit (a large unit for preference) and from OB cut off OE = 1·33 units.

Draw EF perpendicular to OB, cutting OC at F.

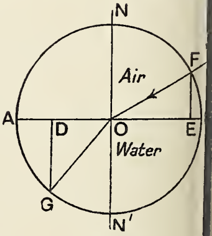


FIG. 24/8

With centre O and radius OF describe a circle. From D draw DG perpendicular to OA, cutting the circle in G. Join OG. Then OG will represent the refracted ray, and the angle GON′ will be the requi angle of refraction (41°).

Proof. CO is the incident ray. To prove that OG is the fracted ray we shall have to show that $\frac{\sin \text{NOF}}{\sin \text{N'OG}} = 1·33$.

$$\text{Now } \frac{\sin \text{NOF}}{\sin \text{N'OG}} = \frac{\sin \text{OFE}}{\sin \text{OGD}} \text{ (alt. angles)} = \frac{\text{OE}}{\text{OF}} \div \frac{\text{OD}}{\text{OG}}$$

$$= \frac{\text{OE}}{\text{OD}} \text{ (for OF = OG)} = 1·33.$$

$\therefore$ OG is the refracted ray, and GON′ is the angle of fraction. Measuring $\angle$GON′ we find it to be **41°**.

Experiments with prisms. It is sometimes stated that when ray of light passes from a rarer medium to a denser one it is fracted towards the normal, and vice versa. Thus (Fig. /9) as the ray AB passes from air to the denser glass it is fracted *towards* the normal BN, while when it passes from ass to air it is refracted *away from* the normal CN′.

The 'rule' has a great many exceptions, but it applies in number of common and important cases—air and glass, and water, water and glass, and (a very important case) en light is passing into cold, dense air from hotter, less dense —so it is worth remembering.

Our 'dense' medium so far, whether consisting of a plate glass or a trough of water, has always had two parallel

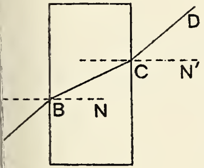


Fig. 24/9

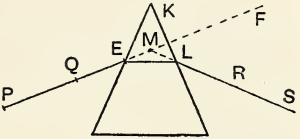


Fig. 24/10

es (as in Fig. 24/9), with the result that the ray has finally erged in a direction parallel to its original one.

glance at Fig. 24/10 shows that this will not be the case e use a triangular prism. In this case the ray that emerges kes a considerable angle with the incident ray (FMS in the re). This angle between the original and final directions he ray is known as the *angle of deviation* (*Lat.* de = from, = a path)—a very good term, because it really does show angle through which the ray has been turned from its inal path.

should be noticed that when, in connection with refraction, speak of the *angle* (or *refracting angle*) of a prism, we mean angle between the two faces at which the light enters leaves the prism respectively. Thus in Fig. 24/10 the acting angle is K.

he greater the angle of the prism, the greater the angle eviation. This is illustrated in Figs. 24/11*a* and 24/11*b*.

We shall refer back to this point when we consider the w in which a lens acts.

Tracing the path of a ray of light through a prism (eit by calculation or by a graphical method) is an excell exercise in refraction. Let us work through such an exerci

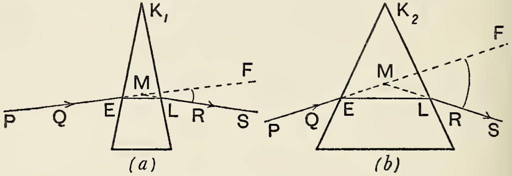


Fig. 24/11

Example 2. *Draw a large diagram showing the path of a nar parallel beam passing through an equilateral glass prism i direction parallel to the base. Indicate on the diagram the angl deviation* (*refractive index of glass* = 1·5).

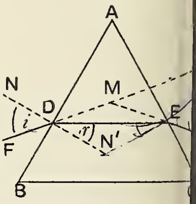


Fig. 24/12

Suppose the beam strikes the face AB at the point D.

It passes through the prism by the path DE, parallel to the base BC.

We must now find the angle at which the ray *enters* the prism—i.e. the angle i which the incident ray makes with the normal NDN′.

The angle of refraction EDN′ or r is 30°. For $\angle B = 60°$.

$\therefore \quad \angle EDB = 120°.$

$\therefore \quad \angle EDN' = \angle EDB - \angle N'DB = 120° - 90° = 30°.$

Now $$\frac{\sin i}{\sin r} = \mu.$$

$$\therefore \quad \sin i = \mu \times \sin r = 1{\cdot}5 \times \sin 30° = 1{\cdot}5 \times 0{\cdot}5 = 0{\cdot}75$$

$\therefore \quad$ (from tables) $i = 48\frac{1}{2}°$.

We therefore make an angle NDF of $48\frac{1}{2}°$ and this gives us incident ray FD. From the symmetry of the figure it can ea be shown that the refracted ray EG is obtained by mal $\angle CEG = \angle BDF$.

The angle of deviation is PMG.

Another solution We can also solve the problem geometrically. ·aw the refracted ray DE as before. The construction is now nilar to that in Example 1 (p. 268), except that there we were ·en the direction of the incident ray and had to find that of e refracted ray, while here it is the other way about. Try to ish the exercise for yourself.

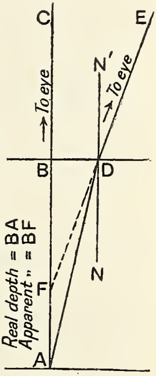


Fig. 24/13

Apparent depth of water. On p. 263 we v that, owing to refraction, the apparent pth of water is less than its real depth. e will now try to find out *how much* less.

Suppose BD is the surface of the water l A a point at the bottom. Let AB be ·ay of light striking the surface normally, l therefore continuing without change direction along BC. AD is another ray eting the surface at D and refracted ng DE. AD is so close to AB that the ·acted rays BC and DE both enter an eye ced at CE.

Produce ED to meet BA at F. Then to eye, A appears to be at F, and FB is the parent depth.

Ve must now try to find the relation between AB (real th) and FB (apparent depth). Draw the normal DN′.

Let μ be the refractive index of water.

$$\mu = \frac{\sin N'DE}{\sin NDA} = \frac{\sin BFD}{\sin BAD} \text{(by parallels)} = \frac{\frac{BD}{DF}}{\frac{BD}{DA}} = \frac{DA}{DF}$$

ut as the angle BAD is very small, $\frac{DA}{DF} = \frac{BA}{BF}$ (approx.)

$$\therefore \quad \mu = \frac{BA}{BF} = \frac{\textit{real depth}}{\textit{apparent depth}}.$$

his relationship would be true for any substance.

1 the case of water, $\mu = \frac{4}{3}$

$$\therefore \quad \frac{\textit{real depth}}{\textit{apparent depth}} = \frac{4}{3}$$

$$\therefore \quad \textit{real depth} = \textit{apparent depth} \times \tfrac{4}{3}.$$

In Fig. 24/13 the rays from A are supposed to strike t surface normally, or very nearly so—i.e. the eye is suppos to be looking vertically downwards. It can be shown th the more obliquely the rays enter the eye, the nearer to t surface will the point F be. That is why, as you walk aw from (say) a trough of drinking-water for horses, it appe to become shallower, while as you walk towards it, it see to grow deeper.

Another method of finding μ. Since $\mu = real\ depth \div$ *parent depth*, and real depth is easily measured, it follows th if in some way we can determine the apparent depth we c find the refractive index.

The experiment is carried out as follows. We will water as the liquid, but the method could be applied to a transparent liquid or (with a little modification) to a tra parent solid such as glass.

Drop a nail into a gas jar or measuring cylinder, which is th nearly filled up with water. Looking vertically downwards i the water, the nail (A) will appear to be at A′, and we have to f the position of A′.

Clamp a knitting-needle K some distance above the surface of the water. Looking downwards, an image of K can be seen, formed by reflection in the water. By moving the clamp, raise or lower K until its image coincides with A′. This is determined by the method of parallax. On moving the head from side to side, A′ and the image of K should cling together.

The distance of the image of K below the surface S of the water is, of course, equal to the distance of K itself *above* the surface. Thus KS gives us the required apparent depth, and $\mu = AS \div KS$. By filling the jar to different depths, other answers may be obtained.

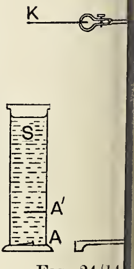


Fig. 24/14

For a transparent solid, the method is slightly modifie

Draw a straight line AB on a sheet of paper and lay a sla glass centrally over it as shown in Fig. 24/15. Stick a pi vertically at a point on the line, and so that it touches the gl Paste a strip of paper centrally on the upper face of the s above AB. To avoid confusion, this strip is not shown in figure.

Now look through the glass in the direction BA. The will appear to be in some such position as C′. To find C′ m

encil point along the strip of paper until, by the method of illax, the pencil point is found to coincide with C′. Mark this tion.

easure the distance from the 'pencil-point position' to that of the slab facing B, so getting the 'apparent depth.' The depth' is, of course, the full length of the slab, and by ding the first measurement into the second, we obtain μ.

xample 3. A microscope is focused on a scratch on the bottom of ystallising-dish. The dish is filled with liquid, and the micro- e has to be raised 1·8 cm. to re-focus the scratch, and a further m. to focus a speck of dust on the surface of the liquid.

lculate the refractive index of the liquid, deducing any formula use in the calculation. O.C.

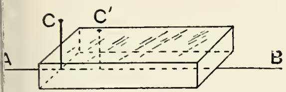


FIG. 24/15

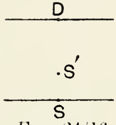


FIG. 24/16

t S (Fig. 24/16) be the true position of the scratch, S′ its rent position, and D the speck of dust on the surface. ently

$= 1{\cdot}8$ cm. and $S'D = 3{\cdot}6$ cm. $\therefore SD = SS' + S'D = 5{\cdot}4$ cm.

$$\mu = SD \div S'D = 5{\cdot}4 \div 3{\cdot}6 = \mathbf{1{\cdot}50}.$$

e latter part of the question was worked out on p. 271.

itical Angle and Total Reflection. Suppose a ray of light velling from air into an optically denser medium [1] such ater. The angle of refraction is less than the angle of ence, and so for any given angle of incidence, there is ys a corresponding angle of refraction. A few cases are sented in Fig. 24/17. AO, BO, CO and DO are incident and Oa, Ob, Oc and Od the corresponding refracted For DO the angle of incidence is 90° (or as near 90° n be shown in a diagram). We can calculate r the sponding angle of refraction, for since $\mu = \frac{4}{3}$ we have

$$\frac{\sin 90^\circ}{\sin r} = \frac{4}{3}$$

$$\sin r = \frac{3}{4} \times \sin 90^\circ = \frac{3}{4} \times 1 = 0{\cdot}75$$

(from tables) $r = 49^\circ$ (approx.)

[1] e. one which will cause the ray to be refracted towards the normal. a medium is often (as in this case) physically denser, but by no always.

It appears, then, that as the angle of incidence incre from 0° to 90°, the corresponding angle of refraction incre from 0° to 49°.

Now let us imagine the direction of the light to be reverse e.g. bO is now the *incident* ray, giving rise to OB as *refracted* ray. cO is refracted as OC and dO as OD. T when the angle of incidence is 49°, the angle of refractio 90°, and cannot be any bigger. The refracted ray just skims the surface.

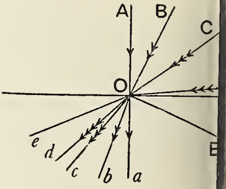


FIG. 24/17

What will happen then with a ray such as eO, where the angle of incidence is greater than 49°?

Such a ray cannot cross the boundary into the second medium at all. It is 'totally reflected' from it. In the diagram eO is shown reflected as OE, the angles eOa and EOa being equal in accordance with the ordir law of reflection.

If instead of the two media being water and air, they d been glass and air, we should have arrived at the same gen l results—i.e. *any* ray of light travelling in air would have b n able to penetrate the glass, no matter what the angl f incidence; but a ray of light travelling in glass can penet e the air only if the angle of incidence does not exceed a cer n value. Given that in this case $\mu = 1{\cdot}5$, we can easily calcu e this 'certain value.' Let it be i. As it is the *biggest pos le* angle of incidence, the corresponding value of r is 90°.

$$\therefore \qquad \frac{\sin i}{\sin 90^\circ} = \frac{1}{1{\cdot}5}\,^{1}$$

$$\therefore \qquad \sin i = \frac{1}{1{\cdot}5} \times \sin 90^\circ = \frac{1}{1{\cdot}5} \times 1 = 0{\cdot}667$$

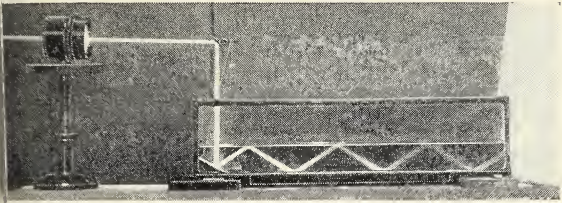
$$\therefore i = 42^\circ.$$

In the case of glass and air, then, 42° is the greatest pos le

[1] $\frac{1}{1{\cdot}5}$, not 1·5. When we say $\mu = 1{\cdot}5$, the ray is understood be passing from air to glass, and thus $\sin i \div \sin r = 1{\cdot}5$. If we revers direction, i becomes r and r becomes i, and so $\frac{\sin r}{\sin i} = 1{\cdot}5$ or $\frac{\sin i}{\sin r} =$

ıgle of incidence for which a ray can penetrate the other edium. If the ray is incident at an angle greater than 42° will be totally reflected.

When a ray of light is travelling through a medium A towards optically less dense medium B, the greatest angle of incidence r which refraction is possible is known as the critical angle the two media.



PHOTOGRAPH OF AN EXPERIMENT SHOWING SEVERAL TOTAL REFLECTIONS AT THE SURFACE OF WATER

Note that the ray that finally issues is refracted.

From 'The Universe of Light,' by Sir William Bragg.

Jnless there is some statement to the contrary, 'B' is lerstood to be air. Thus we say that for water the critical le is 49°, and for glass 42°.

Notice that *two* conditions (implied in the definition just en) must be present before we can have total reflection.

1) The direction of the light must be towards the optically less dense medium.

2) The angle of incidence must exceed the critical angle.

xample 4. *Calculate the critical angle for diamond, given that ndex of refraction of this substance is* 2·42.

et i be the required critical angle.

hus the corresponding angle of refraction, r, is 90°.

$$\frac{\sin i}{\sin 90^\circ} = \frac{1}{2{\cdot}42}$$

ut $\sin 90^\circ = 1$

$$\sin i = 1 \div 2{\cdot}42 = 0{\cdot}413$$

$$i = 24\tfrac{1}{2}^\circ.$$

T

Owing to this small critical angle, rays of light which ent
a diamond are for the most part reflected from the next fa
they meet—often from a whole succession of faces—and it
this which gives a diamond its characteristic sparkle.

***Example* 5.** *Find the above angle by means of a geometric construction.*

All we have to do is to construct an angle whose sine is $\frac{1}{2{\cdot}42}$

From A draw a straight line AB of unlimited length. Dr
AC perp. to AB and of length 1 unit (Fig 24/18).

With centre C and radius 2·42 units draw an arc of a cir
cutting AB in D. Join CD.

Then CDA is the required angle, for sin CDA = CA ÷ (
= 1 ÷ 2·42 which is the required value.

On measurement, CDA should, of course, be found to be 24½

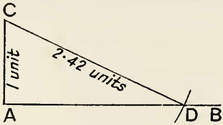


FIG. 24/18

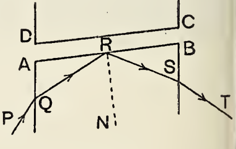


FIG. 24/19

Examples of Total Reflection. Some of these have alrea
been discussed in *Junior Physics* (pp. 240–2), and need o
be recalled briefly. ABCD (Fig. 24/19) represents (with gr
exaggeration) the narrow air-space produced when glass
cracked. Rays of light such as PQR are totally reflected (
angle QRN being greater than 49°, the critical angle),
the crack is seen as a brilliant gleam.

The *mirage* often mentioned by desert travellers i
consequence of total reflection.

In contact with the hot ground, the air itself becomes h
but at points farther and farther from the earth the
becomes cooler and cooler (and therefore denser and dens
Thus rays of light travelling downwards from an object s
as A are constantly travelling from a denser medium t
rarer one, and so are refracted away from the normal (
24/20). At the same time the angles of incidence (i_1, i_2 .
are constantly increasing, and when the critical angl

ached the ray begins to bend upwards (at B in Fig. 24/20). o the eye, A seems to be at A′ and the sky itself gives a irage looking very like a pool, in which A (seen directly rough the cool upper layers of air) appears to be reflected. ius the traveller is deluded into thinking that he is approaching a pool of water with palm trees on the banks. The tree real enough, but not the pool.

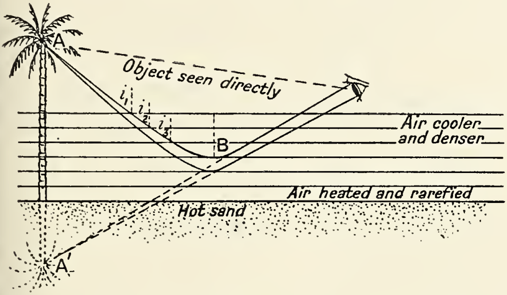


Fig. 24/20

Vhen walking along a straight asphalted road in England a hot day one can often see an apparent pool of water in distance. Here the object seen as a mirage is the sky.

Fig. 24/21 shows how a glass prism of angles 90°, 45°, 45° y be used to deflect a ray of light ough a right angle. This principle a number of applications—e.g. in the iscope of a submarine, by which ships, , may be easily observed, though the marine itself is submerged except for top of its periscope.

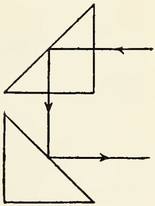


Fig. 24/21

'prism' mirror, for some purposes, has ain advantages over the ordinary l. The latter tends to give confusing tiple images (*Junior Physics*, pp. 237– f the silvering is at the back, while if it is at the front it asily damaged. The prism mirror, of course, requires no ering, and it gives a single sharp image.

Questions

A

1. When a lighted candle is held in front of a thick plate-gla mirror several images can be seen, one of which is much bright than the others. Explain.

2. Draw a diagram to explain why, to an observer standi beside a swimming-bath, the water appears to be less deep th it really is.

3. Why does a straight rod partly immersed in water appe to be bent at the surface?

4. Explain *critical angle* and *total internal reflection of lig* and give a labelled ray diagram to illustrate a practical applicati of the latter, using as an example a glass prism with angles 9 45°, 45°. *C.W.B.**

B

1. Explain, with the help of diagrams, the terms *refract index* and *critical angle*.

How would you determine the refractive index of glass giv a glass block?

A ray of light is incident in glass on the top surface of a gl block at an angle of incidence of 60°. Assuming the refract index of glass is $\frac{3}{2}$, find the subsequent path of the ray. *Brist*

2. A ray of light makes an angle of incidence of 30° on the fa of a glass prism of refracting angle 60° and refractive index 1 Trace the path of the ray through the prism and measure t angle of deviation.

For what other angle of incidence will the deviation have t same value? *Dur.**

3. Objects frequently appear distorted when viewed throu a pane of ordinary window-glass. On the other hand, th plate glass rarely produces distortion though the object m appear displaced. Explain. *O.C.*

4. How would you determine the refractive index of a liqui

A prism, refractive index 1·5, has a side AB of 5 cm. and angles at A and B are 45° and 60° respectively. A parallel be of light of width 4·5 cm. falls normally on AB so that the ed of the beam are 0·25 cm. from A and B. Give a construct showing the paths of the following rays through the prism the two extreme rays, (*b*) the central ray. *Dur.*

5. Define *refractive index.*

Describe in detail how you would find (*a*) one of the angle a triangular glass prism by an optical method, (*b*) the refract index of the material of the prism. *Lond.*

6. Explain with the help of a diagram why the apparent depth a pond is less than its true depth. Deduce the expression for e refractive index of a substance in terms of real and apparent pths. Describe an experiment to determine the refractive dex of water which makes use of the relation between real and parent depths. *Lond.*

7. A soot-covered ball when immersed in water appears brightly lished. Why?

3. A parallel beam of light falls on the surface of water at an gle of incidence of 60°. Find, by a graphical construction or herwise, the path of the beam after it meets the water surface he incident beam is (*a*) in air, (*b*) in water.
Refractive index of water = 4/3.) *Lond.**

). On a warm sunny day, dry tarmac roads frequently appear be covered with pools of water, which dry up as the pools are proached. Why? *O.C.*

.0. The following corresponding values of the angle of idence i in air and the angle of refraction r in water were ained:

$i°$.	10·0	20·0	30·0	40·0	50·0	60·0
$r°$.	7·5	14·8	22·0	28·75	35·15	40·5

Jse these readings to obtain a straight line graph and hence ulate the refractive index of water. Draw a labelled diagram show how you might get such a set of results yourself. You y use any special apparatus, and should give a brief description. *Camb.*

1. A ray of light in air meets the surface of a rectangular glass k at an angle of incidence of 45°. It is refracted so that it ts next one of the surfaces at right angles to the first. Find direction on leaving this face. (Refractive index of glass ·5.) *J.M.B.**

2. Rays of light are emitted upwards in all directions from oint at the bottom of a swimming pool where the depth of er is 3 feet. Show that when the water is still all rays which t the surface outside a certain circle will be totally reflected. ere is the centre of this circle and what is its radius?
Refractive index, air to water = 1·33.) *Dur.**

CHAPTER 25

REFRACTION AT CURVED SURFACES

In ancient times—at least as early as 400 B.C.—the Greel had either discovered for themselves or had copied fro others the art of making a 'burning-glass.' This was shap like Fig. 25/1*a* or *b*. You will notice that Fig. 25/1*b* roughly the shape of a lentil seed, and the Latin word f lentil is *lens*. That is how such glasses came to be call lenses.

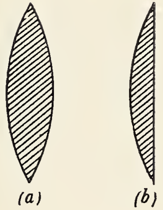


FIG. 25/1

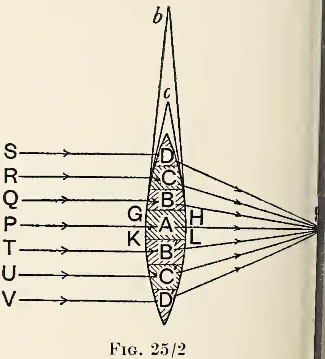


FIG. 25/2

A glass of this sort 'burns' because it causes rays of h from the sun to be brought together to a point called t *focus* (*Lat.* focus = hearth—a hot place). Rays of light affected in the same way, and it is important to notice w a lens should have such a curious effect. Suppose para rays of light from the sun are striking the lens as shown Fig. 25/2, and imagine the lens to be divided into sectio such as A, B, C, D.

Each of these sections is a portion of a prism, except t its sides are slightly curved instead of being plane. Fig. 25/2 we have produced the nearly straight sides of B *b*, making a complete prism B*b*. We have also shown

mplete prism C*c*. We can easily see from this figure that e prism B*b* is longer and sharper than C*c*—it is a prism *smaller angle*.

Now, on p. 269 we saw that a prism causes a ray of light undergo a change of direction—to be deviated—and that e greater the angle of the prism, the greater will be the viation it produces. Hence C, a part of the prism C*c*, will oduce more deviation than B, which belongs to a prism of aller angle. For the same reason, D will produce more viation than C.

Now we can see why it is quite possible for all the rays S, Q, etc., to be brought together to the same point. To gin with, the central ray P will undergo no deviation at , because the portion A is *not* a prism, but a plate with its posite faces parallel. Suppose the ray Q, deviated by the ism' B, meets this central ray at F. Can the ray R, viated by the 'prism' C, also pass through F? To do so, it st undergo more deviation than Q, and, of course, that is t what happens, as we have already seen. Similarly, S l need to be deviated even more, which it will be, because s of larger angle than C.

The lenses studied in this chapter will be *spherical*—i.e. curved surface or surfaces will be parts of spheres. With h a lens the increase of deviation needed as we work from centre of the lens to the edge (i.e. from A to D or D′) is accurately secured by the increasing 'angle of prism.' nce the rays do not focus exactly at F. F in fact is a small a rather than a point. The defect is known as *spherical rration.*

erms defined. There are certain terms constantly used he study of lenses, and we had better get clear ideas of m at once.

o begin with the term ***lens*** itself. This might be defined a transparent body bounded by two surfaces of which at t one is spherical. A ***double convex*** lens is one bounded two convex surfaces. One of these is illustrated in Fig. l*a*. If one of the surfaces is plane and the other convex . 25/1*b*), the lens is *plano-convex*. One surface may even oncave and the other convex (Fig. 25/3). In that case lens is *concavo-convex*.

In all cases a convex lens is *thicker at the centre than at t edge.*

We have already seen that the curved surface (or surface of a lens may form part of a sphere (or spheres), and th the lens is then said to be *spherical.* The spheres may or m not be of the same radius. In Fig. 25/4 the right-ha

Fig. 25/3

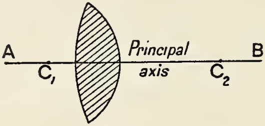


Fig. 25/4

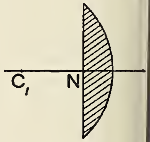


Fig. 25/5

surface forms part of a sphere of centre C_1, and the left-ha surface has its centre at C_2. The straight line joining th centres (AB in the figure) is known as the *principal axis* the lens.

(In the case of a plano-convex lens, the principal a would be the line which passes through the centre of curvatu of the one face and is normal to the other—C_1N in Fig. 25/

We have seen that rays of light parallel to the principal axis are brought to a focus (F in Fig. 25/2). The point is known as the *principal focus* of the lens. It can be shown that it lies on the principal axis.

Owing to spherical aberration, discussed above, it is only those rays of light passing near to the principal axis which actually pass through F. That is why a photographer 'stops down' when he wishes to get an image very sharply focused—i.e. he uses only the cent part of his lens.

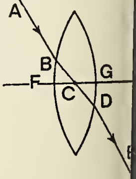


Fig. 25/6

Suppose (Fig. 25/6) a ray AB enters a lens at B and leave at D by the path DE. If the parts of the lens in the i mediate neighbourhood of B and D respectively are paral then for practical purposes the ray is passing through a gl plate with parallel sides, and its final direction DE will parallel to its original direction AB (p. 265)—i.e. there

no *deviation*. There will, however, be some *displacement*, cause DE, though parallel to AB, will not usually be in e with it.

Suppose BD cuts the principal axis at C.

It can be shown that *all* rays of light which emerge from a s in a direction parallel to their original direction pass rough a particular point on the axis (C in Fig. 25/6). This int is known as the *optical centre* of the lens.

If the lens is thin, the optical centre may be taken without ch error as any point on that part of the principal axis ich lies inside the lens—e.g. any point on FG in Fig. 25/6. practice we usually take it as C, the middle point of FG. ain, if the lens is thin, the displacement will be negligible. us a ray of light passing through the optical centre of a n lens passes on its way *as though the lens did not exist at all.* shall see presently that we can make very great use of fact.

The *focal length* of a lens is the distance from the optical tre to the principal focus.

imple method of finding focal length. If we hold up a vex lens L so that it faces the sun, and hold a post-card P the other side, then by moving P we can soon find a position which S, an image of the sun, is focused upon it. The ance CS then gives the focal gth, C being the optical cenof the lens.

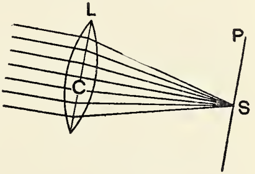


Fig. 25/7

f course we cannot in prachold lenses and post-cards make measurements at the e time. Actually we should port L in a lens-holder and vith the clamp of a retort d. A square of three-ply ted white is better than a post-card, because it is much e rigid.

gain, we often use the laboratory window-frames, perhaps r 20 ft. away, instead of the sun. As mentioned on p. 234, light from these is parallel for practical purposes, and ept on a really dull day) by using them it is easier to in an accurately focused image.

Other methods of finding the focal length of a lens a described on pp. 286–7.

Problems solved graphically. We now have sufficie knowledge of convex lenses to work out certain problems graphical methods, or by methods involving easy geomet (usually similar triangles).

Example 1. *In the experiment just mentioned, a window-fra gives an image* 1·2 *in. long. The distance from the window-fra to the lens is* 12 *ft., and from the lens to the image* 7·2 *in. Find focal length of the lens and the length of the window-frame.*

The focal length of the lens is obviously **7·2 in.** (positi because a *real* image is formed at the focus).

Now consider Fig. 25/8 (not drawn to scale), in which AB is the frame, A′B′ the image, and C the optical centre of the lens. DCE is the principal axis. The ray AC passing through the centre has undergone no deviation—i.e. ACA′ is a straight line. Similarly BCB′. As AB is parallel to A′B′ it follows th $\angle A = \angle A'$, $\angle B = \angle B'$ and so ABC and A′B′C are simi triangles.

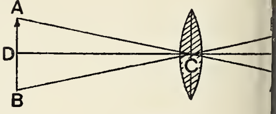


FIG. 25/8

$$\therefore \qquad \frac{AB}{A'B'} = \frac{BC}{B'C} = \frac{DC}{CE} = \frac{12 \text{ ft.}}{7{\cdot}2 \text{ in.}} = \frac{144 \text{ in.}}{7{\cdot}2 \text{ in.}} = 20$$

$$\therefore \qquad AB = 20 \times A'B' = 20 \times 1{\cdot}2'' = \mathbf{2\ ft.}$$

Example 2. *A small object,* $\frac{1}{2}$ *in. high, stands on and perpendicu to the axis of a convex lens, and a real image* $1\frac{1}{2}$ *in. high is forn on a screen* 12 *in. from the object. Make a scale diagram of arrangement, and from it (or otherwise) find the distances of object and image from the lens, and the focal length of the le*
Lond.

Draw the axis AA′, the object AB $\frac{1}{2}$ in. high, and the ima A′B′ $1\frac{1}{2}$ in. high (a real image formed by a convex lens is alw inverted). AA′ must represent 12 in., but it will be convenient to make horizontal measurements to half-scale as compared with vertical.

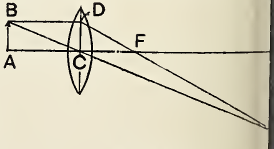


FIG. 25/9

Join BB′ cutting the axis at C. This will be the optical centre of the lens, which we can now insert in our diagram. From B draw BD parallel to

axis, cutting the lens at D. We know that B′ is the image ꞊, and therefore the ray BD parallel to the axis must be re- ted in the direction DB′. Further, this refracted ray passes ugh the focus, which is therefore at F, where DB′ crosses axis.

y measurement we find that

distance of object from lens, CA $=$ **3 in.**
,, ,, image ,, ,, CA′ $=$ **9 in.**
focal length of lens ,, ,, CF $=$ **$2\frac{1}{4}$ in.**

onjugate Foci. Going back to Fig. 25/9, suppose A′B′ the *object*. To get the image of B′ we could draw (i) ray B′C which would proceed along the path CB without ge of direction, (ii) the ray BFD which would be refracted g DB. Thus B would be the image of B′.

pair of points such as B and B′ so placed in relation to s[1] that if either of them is regarded as the object the other e image, are known as ***conjugate foci.***

portant lens formula. We should expect that there be some purely mathematical method—independent of

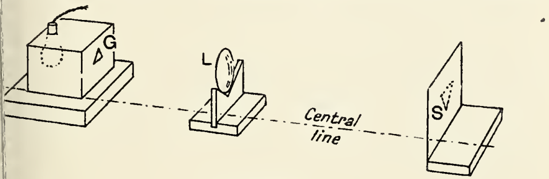


Fig. 25/10

drawing—of solving problems such as those considered e examples just given. That is the case, and it can be n that provided we observe the *real-is-positive* con- on (p. 244) the formula already used for mirrors applies ses—i.e. $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$.

ification of formula. To prove experimentally that the la just mentioned holds for a convex lens, we may use y-box. A straight line is chalked on the bench, and the line of the box is placed over this (Fig. 25/10). The of the box consists of a piece of three-ply, out of which ngle has been cut to take a piece of wire gauze G. A

[1] The same applies to a mirror.

convex lens L of focal length about a foot and suita[b]
mounted, is placed about 2 ft. from the box front, and beyo[nd]
this again is a screen S.

S is moved nearer to L, or farther from it, until a shar[ply] defined image of G is obtained. We then carefully meas[ure] the distances LG ($= u$) and LS ($= v$). The focal length [is] found by the modification of the 'sun' method descri[bed] on p. 283.

The work is now repeated several times (except that f n[eed] not be re-determined), altering the distance LG and th[en] altering the position of S until the image is again shar[ply] focused. The results may be set out thus:

Expt.	LG ($= u$)	LS ($= v$)	f	$\frac{1}{v}$	$\frac{1}{u}$	$\frac{1}{v}+\frac{1}{u}$	$\frac{1}{f}$
1 2 3 etc.							

Determination of focal length. In the experiment [j]ust described, f was found by an independent method, and th[en], from the known values of f, v and u we verified the form[ula]. If, however, we *assume* that the formula is true, we [can] measure v and u as described above, and *calculate* f. In fact, the experiment gives us one of the best methods of finding the focal length of a convex lens.

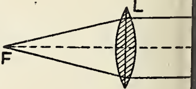


Fig. 25/11

Another method depends on the fact that if a small bright object is placed at F, the focus of a convex lens L, the rays of l[ight] which it gives off will, after passing through the lens, em[erge] parallel. (Imagine the rays travelling in the reverse di[rec]tion, and the truth of this is seen at once.) If then a p[lane] mirror M is placed perpendicular to the axis of the [lens], these emerging rays will be reflected along their own p[ath], and will give an image at F, the image coinciding with [the] object.

To apply this method in practice, we arrange our ray [bo]x

lens as in Fig. 25/10, but instead of a screen we have a
ie mirror, usually placed much closer to the lens than S
Fig. 25/10. We now move the lens until a position is
id in which a sharp image of the triangular gauze is
ned just beside the original. The focal length is then
al to the distance GL.

Iagnification. The **magnification** produced by a lens is
ratio *length of image* $\div$ *length of object*. Suppose, for
ince, that with an optical lantern a slide of 3 in. side
s rise to an image of 6 ft. side, the magnification would be
$\times$ 12) in. $\div$ 3 in. = 24.

can be shown by Geometry that magnification as thus
ied is equal to the ratio v/u, where v and u have their
l meanings.

verify the formula *experimentally*, we go back to the
ngement illustrated in Fig. 25/10 on p. 285. After
ng the image sharply focused, we use a pair of dividers
elp in measuring one side of the gauze triangle, and the
esponding side of the image (not forgetting that the
igle is inverted). Suppose these lengths are S_1 and S_2
ectively. We find that the magnification, S_2/S_1, is equal
$/u$. We then repeat the work with other values of u
v.

two holes of the gauze may be plugged up with bits of
hstick, the distance between the two points being taken
.

ncave Lenses. A characteristic of convex lenses is that
are thicker in the middle than at the edges. A concave
on the other hand, is thinner in the middle.

ree kinds are shown in Fig. 25/12:
le concave, plano-concave and con-
-concave respectively.

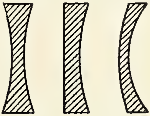


Fig. 25/12

understand the action of a concave
we may suppose it to be divided into
of prisms, A, B, B′, etc., as we did in
ase of the convex lens. Rays of light
R . . . etc., all parallel to the prin-
axis, are represented as falling on these 'prism' portions
25/13).

nparing Fig. 25/13 with Fig. 25/2, we notice that in Fig.

25/2 each prism had its thin end pointing *away* from the cen while in Fig. 25/13 the reverse is the case. As a result, ray light after refraction do not *converge* to a point F, but *div* or spread out fanwise. These diverging rays all appear come from a point F which is thus a *virtual* focus, and so focal length is negative.

In the previous discussion we saw that the portion C instance) produced a greater deviation than B, becaus

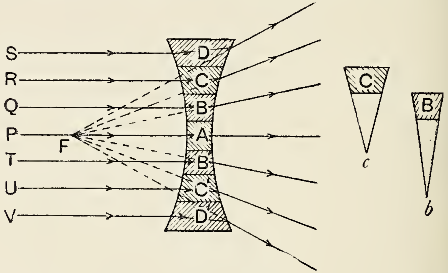


FIG. 25/13

B and C are developed into complete prisms, C will hav larger angle than B. Exactly the same reasoning ap in the present case.

Problems relating to Lenses. We will conclude this cha by considering a few other typical problems relating to le It will be noticed that they may often be solved graphicall

Example 3. *An erect object,* 1 *in. high, is placed* 8 *in. in f of a convex lens, whose focal length is* 6 *in. Determine eithe graphical construction or by calculation the position and heig the image formed by the lens.* J.M.B.*

$$u = 8 \text{ in.} \quad f = 6 \text{ in.} \quad v = ?$$

The equation $$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

becomes $$\frac{1}{v} + \frac{1}{8} = \frac{1}{6}$$

whence $$v = +\ 24.$$

The + sign shows that the image is real. It is therefor the side opposite to the object, **24 in.** from the lens.

Magnification $= v/u = 24/8 = 3$.

As the object is 1 in. high, the image will be **3 in.** high.

aphical method. It will be convenient to work to a scale of 0 horizontally, and 1 : 2 vertically.

aw the lens, and mark its axis and focus F; also its middle Put in AB ($\frac{1}{2}$ in. to represent 1 in.), BC being 0·8 in. epresent 8 in.) and CF being 0·6 in. (to represent 6 in.) 25/14).

ıd the image of A in the usual way (AD parallel to the axis, join DF and produce; join AC and produce, the two lines ıced meeting at A′). Obtain B′ by drawing A′B′ per-icular to the axis.

measurement CB′ is found to be 2·4 in., representing **24 in.** A′B′ is 1·5 in. representing **3 in.**

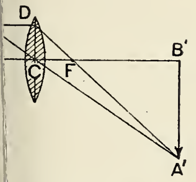


Fig. 25/14

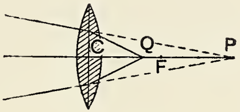


Fig. 25/15

mple 4. *A beam of light is converging to a point* 20 *cm. a convex lens of focal length* 10 *cm., the axis of the beam ling with the principal axis of the lens. Calculate the position point to which the beam converges after passing through the Illustrate by means of a diagram.* Lond.*

source of light is the converging beam. The point to this converges must be regarded as the object, and is virtual—i.e. $u = -20$ cm. The lens being convex has cus, so f (10 cm.) is positive.

ying $$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

e $$\frac{1}{v} + \frac{1}{-20} = \frac{1}{10}$$

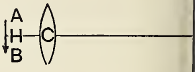
gives $$v = +6\tfrac{2}{3}.$$

e the image is real, the beam converging to the point Q 5/15), where $CQ = 6\frac{2}{3}$ cm.

***Example* 5.** *A convex lens is used to project the image of an o* *on to a screen, which is* 100 *cm. from the object. The object is* 5 *square and the image* 20 *cm. square. Find* (a) *the distance of* *object from the lens,* (b) *the focal length of the lens.* Camb.*

Let AB and A′B′ represent the edges (5 cm. and 20 cm. object and image respectively (Fig. 25/16). The position of lens (centre C) has to be found.

The magnification $= \frac{20}{5} = 4$



$\therefore \qquad \frac{v}{u} = 4$

Fig. 25/16

HC then must be 1/5th of the whole distance HK; i.e. 1/5th of 100 cm. = **20 cm.**

We then have $u = 20$, $v = 80$, $f = ?$

Substituting in the formula $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$

we have $\qquad \frac{1}{80} + \frac{1}{20} = \frac{1}{f}$

giving $\qquad f =$ **16 cm.**

Questions

1. Distinguish between a real image and virtual image. W is meant by the focal length of a convex lens?

An object 1 cm. long is placed 40 cm. from a convex le focal length 10 cm. Find the size and position of the imag means of a ray diagram drawn to scale. Explain your struction.

What other information about the image does the dia give? *Oxf.*

2. The following results were obtained in an experiment a convex lens:

Distance of object from lens, u cm.	25·0	35·0	45·0	55·0	65·0	75·0	8
Distance of real image from lens, v cm.	103·2	47·0	35·9	31·1	28·9	27·3	2

Using your table of reciprocals, plot $\frac{1}{v}$ against $\frac{1}{u}$. Deter the focal length of the lens. *Camb.*

:. A convex lens forms an *erect* image which is four times the ›ar size of the object, the distance between object and image ng 100 cm. Find graphically *or* by calculation the position he lens and its focal length. *Brist.**

. What is meant by the principal focus of a lens?

)escribe one accurate method of determining the focal length convex lens.

n image five times the length of the object is to be projected o a screen which is 72 cm. from the object. What kind of lens st be used, what is its focal length, and where must it be placed? *Camb.*

. Describe how you would determine accurately the focal gth of a convex lens without using a distant object.

convex lens of focal length 10 cm. is used to read the luations on a scale, and it is held so that an upright image, ›se size is 5 times that of the object, is formed. How far n the scale is the lens held? *Camb.*

. Write down a formula relating image distance (v), object ance (u), and focal length (f) for a lens. State a convention erning the signs to be given to these distances, and apply it he formula to find the position of the image of an object ed 40 cm. in front of a *concave lens* of focal length 20 cm. Is image (a) real or virtual, (b) erect or inverted?

raw a ray diagram showing two rays from a point on the ct to the eye of an observer. *Camb.*

Explain, with the help of a carefully drawn diagram, the nation of an image by a *concave lens*.

concave lens has a focal length of 15 cm. Find the position he image of an object placed 20 cm. in front of it. State ther the image is (a) real or virtual, (b) erect or inverted.

ention one common use of a concave lens and briefly explain *Camb.*

CHAPTER 26

SOME OPTICAL INSTRUMENTS

WITH a little thought we soon realise that many instrume of great practical use depend for their action on the prese of one or more lenses. There is the simple 'reading-gla the camera, the telescope and microscope and the proje used at the 'pictures.' Among the simplest and yet the m important we have the humble pair of spectacles. There millions of people in the world who without them would completely cut off from the pleasures of reading, and ot millions who would be unable to see clearly anything a distance.

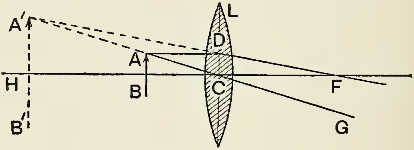


FIG. 26/1

The lens is an essential feature of many other instrume but those mentioned will serve as a fair sample.

The Simple Microscope. This is much used as a read glass or pocket-lens. It consists of a convex lens, whic use must be placed at a shorter distance from the object t its own focal length. In this position it gives an er enlarged, virtual image as shown in Fig. 26/1.

The eye is supposed to be just to the right of the lens, to get the best results we move the lens about so as to b A′B′ as near as possible to the eye. But there is a limi this nearness. You know that if you are examining a s object, and you put your eye *very* close to it, you ca 'focus' it—you cannot see it distinctly. The shortest dist at which you can see the object clearly is known as *the ne distance of distinct vision.* In an average case this is al 10 in.—less for young people and much more for the mi aged and old.

We move our lens then, until A′B′ is at this nearest distance distinct vision.

Example 1. A person can see clearly any object which is 10 *in. further) from his eye. Make a ray diagram to show how he ld best use a simple magnifying glass of focal length* 4 *in. and l by measurement the magnification obtained.*

Ve do not know the position of the object, but we know that image A′B′ must be 10 in. from the lens. So we begin by wing the lens (centre C), its principal axis HCF, and the image 3′ (any convenient length) 10 in. from C. We also mark F ' = 4 in.).

Comparing our incomplete gram with Fig. 26/1, we see t we have to find the posi- n of the object AB. The struction is fairly obvious. w A′CG. Join A′F cutting middle line of the lens in D. n draw DA parallel to the s, cutting A′CG in A. This es us the position of the top

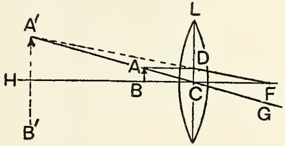


FIG. 26/2

nt of the object (for a ray AD, parallel to the axis, is ig refracted through F) and we can easily draw AB.

y measurement, we find that the object must be **2·9 in. from lens,** and that the **magnification,** $\frac{A'B'}{AB} = 3\frac{1}{2}$.

he Camera. We have just seen that in the simple micro- pe the distance from object to lens must be *less* than focal length of the lens. If it is greater we get quite a erent effect (cf. Fig. 25/9, p. 284). The image is now rted and *real*—it can be received on a screen. Here we e, very simply, the principle of the camera, of the human and of the projection lantern or optical lantern ('magic ern').

he camera was described in some detail in our earlier book, ve shall content ourselves now with little more than a ram; but the diaphragm (Fig. 26/3*b*) calls for further ce. If the light is poor, the photographer will probably e it fully open, but there is one disadvantage in this. On 31 we saw that an ordinary lens is subject to a defect known *pherical aberration*—the rays striking the outer portions of lens do not come to a focus at quite the same point as e passing through the central part. As a result, the

image formed by a fully open lens is slightly blurred. If th
photographer wants a very sharply focused image, he 'stop
down'—i.e. adjusts the diaphragm so that only the centr
part of the lens is in action. In this case, to make up for th

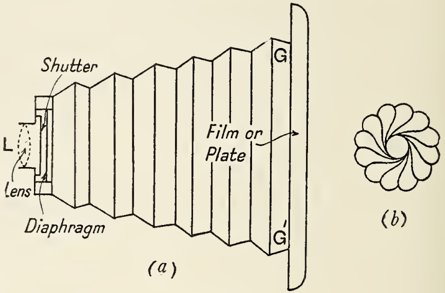


Fig. 26/3

smaller amount of light passing through the lens, he must, course, give a longer exposure.

The Epidiascope. This instrument is often used in schoo for giving an image of an object (such as a printed pag picture, map, etc.), without first preparing a slide. T object AB is very brightly illuminated, and the rays of light from it pass through a convex lens placed above it at a distance greater than the focal length. They are then reflected from a mirror silvered at the front (to avoid multiple images) and come to a focus on the screen.

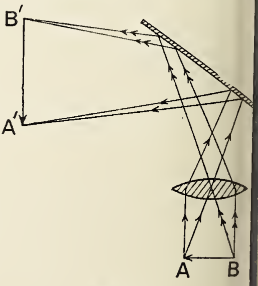


Fig. 26/4

The Eye. The structure of the eye will be clear from Fig. 26/5. Most of its parts have already been discussed (*Junior Physics*, pp. 256–7), but one or two points may now be added. T *choroid* is an inner coating which lines the outer coveri

e sclerotic), except in front. The inner side of the choroid tains a dark pigment to prevent reflection of light. ached to the choroid we have the *suspensory ligament*, ., which holds the crystalline lens in position. The part he eye in front of the lens, suspensory ligament, etc., is d with a liquid called the *aqueous humour* (A.H.) and the k part with a more gelatinous liquid known as the *vitreous iour* (V.H.). From the retina, impressions are conveyed he brain through the *optic nerve*. The point at which the er enters the eye is known as the *blind spot*, because it is

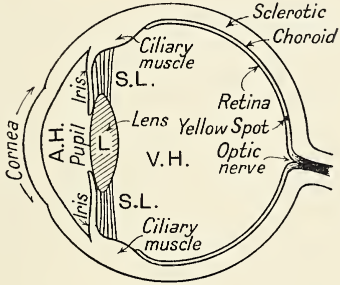


FIG. 26/5

ensitive to light. The part most sensitive to light is the *v spot*, near the centre of the retina.

mparing the eye with the camera, we see that in both are (i) a lens, (ii) a diaphragm, with an aperture of table size to admit more or less light, (iii) a screen, (iv) itter (the eyelid) and (v) a black coating on the inside o prevent internal reflection.

e chief difference lies in the method of focusing. In the ra, this is done by altering the distance between the and the screen. In the eye, it is done by altering urvature of the lens. When we are looking at a it object, the ciliary muscles are relaxed, and the has its minimum of curvature. If now we wish to ve a near object, the muscles tighten, and the lens

assumes just the degree of curvature necessary to give sharp image.

This power possessed by the eye of altering the curvatu of its lens is known as *accommodation*, or *accommodative pow* Towards middle life there is a marked falling off in acco modative power. A man can still see distant objects clear but cannot see to read without the help of spectacles.

Thus in Fig. 26/6 (a) rays of light from a distant obj A are practically parallel, and the lens of the man's eye able to bring them to a focus on the retina. Fig. 26/6 represents a much nearer object. The rays from this are rather sharply divergent, and though the eye-lens turns them inwards as before, it is not able to overcome their original divergence sufficiently to bring them to a focus on the retina.

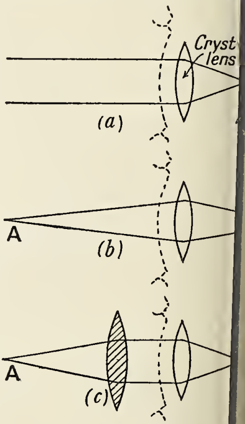


FIG. 26/6

If, however (Fig. 26/6 (c)), a convex lens is placed in front of the eye of such focal length that the rays leave it in a parallel direction, then the eye-lens will do the rest as in Fig. 26/6 (a).

Suppose A represents print which the man wishes to read at a distance of, say, 10 in. Clearly all he needs is a convex lens of focal length 10 in.

We can put this in another way. An object whic is really 10 in. away must give an image at infinity (the par el lines to the right of the convex lens, produced backwa s, meet at infinity). So $u = 10$, $v = \infty$ and f is to be fo d. Employing the usual formula $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$ we have $\frac{1}{\infty} + \frac{1}{10}$ $\frac{1}{f}$.

But $\frac{1}{\infty} = 0$ and so $f = 10$, i.e. we need a convex lens of al length 10 in.

What we have just discussed represents an extreme ca — that the man's crystalline lens has *no* accommodative p r.

practice it nearly always retains a certain amount. Suppose can clearly distinguish objects at a distance of 4 ft., but t nearer (i.e. his *near point* is 4 ft.), and he wishes to be le to see things (e.g. print) at a distance of 1 ft. What rength of lens will be required?

Rays from a point which is really 12 in. from the lens ust seem, after passing through it, to come from a point in. away—i.e. $u = 12$, $v = -48$; $\therefore \frac{1}{v} + \frac{1}{u} = \frac{1}{f}$ becomes $\frac{1}{48} + \frac{1}{12} = \frac{1}{f}$ from which $f = 16$, so he needs a convex lens 16 in. focal length.

A defect somewhat similar to the above is *long sight.* Here power of accommodation may be normal, but the eyeball oo thin from back to front. The result is that even when eye is using all its power accommodation, rays that re passed through the crystal- lens have not been brought a focus by the time they ch the retina.

To correct the defect, a con- lens is used as already cribed.

ther defects of vision. An- er very common defect of on is *short-sight,* or *myopia.* this case, perhaps owing some muscular weakness, eyeball has become somewhat bulged, and is too long front to back. The result is that rays of light are ight to a focus in front of the retina, instead of on it (Fig. a).

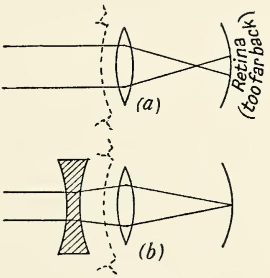


Fig. 26/7

o put a convex lens in front of the eye would only make ters worse, for the rays of light which have passed through crystalline lens are already too convergent, and this would e them more so. The remedy is evidently to use a ave lens (Fig. 26/7*b*). This increases the *divergency* of rays which strike the crystalline lens, and therefore they ot converge so quickly after they leave it.

***Example* 3.** *A short-sighted man has distinct vision only up 4 ft. What must be the focal length of lenses which will enable hi to see distant objects distinctly?*

The rays of light (AB, CD) which reach the eye from a dista object will be practically parallel. We need a lens such th after the rays have passed through it, they seem to come from point P 4 ft. away (Fig. 26/8). What we need is a concave le of focal length **4 ft.** (really − 4 ft.).

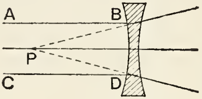


Fig. 26/8

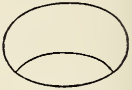


Fig. 26/9

Or we may use our formula $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$. $v = -4$ ft. and the object is distant we put $u = \infty$ so that $\frac{1}{u} = 0$.

Then $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$ becomes $-\frac{1}{4} + 0 = \frac{1}{f}$ whence $f = -$ **4 ft.** as befo

It oftens happens, especially with elderly people, that owi to loss of accommodative power, they can see neither obje that are very distant, nor very near. In this case two pa of spectacles are needed. You may know somebody w uses one pair of spectacles for 'the pictures' and another p for reading. Very often the two pairs are combined in o known as 'bifocals' (Fig. 26/9) the lower part of the glass be used for reading.

The Astronomical Telescope. The best way to underst the principle of the astronomical telescope is to proceed follows with two convex lenses, one of very short focal len say 2 in., and the other of focal length about a foot.

At one end of the laboratory pin a page of fair-sized print, say a handbill, upside down (H in Fig. 26/10). Fix the long-focus lens in a holder at L_1, the distance HL_1 being considerable, say 10 ft. or more.

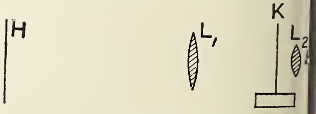


Fig. 26/10

Standing well back from L_1 you will see a real, inverted im of the handbill. Mark the position of this image by mean

nitting-needle K stuck into a wooden block, using the method parallax (p. 230).

Now place the short-focus lens L_2 about 2 in. from the knitting-dle, and putting your eye close to it, adjust its position until get a clear large view of the needle—i.e. use the lens as a ple magnifying glass. As the real image of the print is in position K, you should now have a clear image of the handbill. practice, you may find it necessary to re-adjust L_2 just a little. Fig. 26/11 we trace the rays by which the handbill is seen.

The first lens gives us the real, inverted image A′B′. The ance of this from L_2 is less than the focal length of L_2, so we obtain a virtual image A″B″ erect with respect A′B′, but inverted with respect to AB.

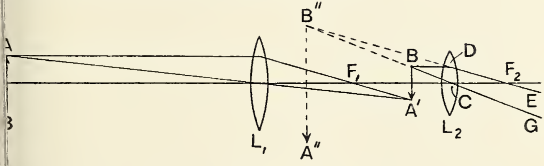


FIG. 26/11

ig. 26/11 will serve to illustrate the action of the astro-ical telescope if we understand that AB is really enormously ant, and in that case the image A′B′ passes through the cipal focus of L_1 (cf. the 'sun' method, p. 283, for finding focal length of a lens). Again, in an astronomical rvation, the distance of A′B′ from L_2 is equal to the focal th of L_2. This causes emergent rays such as DE and CG e parallel and so A″B″ is formed at infinity. The lens nearer to the object is known as the *object glass*, and the r lens, nearer to the eye, as the *eye piece*. From what has said, it will be clear that the distance between the object and eye piece in an astronomical telescope is equal to sum of their focal lengths.

agnification. The definition that *magnification* = (*length nage*) ÷ (*length of object*) (p. 287) does not carry us very because we have no direct means of finding either of these hs. An alternative definition is adopted, viz. *magnifica-* = (*angle subtended at the eye by image*) ÷ (*angle sub-d at the eye by object*), and it can be shown from this

that *magnification = focal length of object glass ÷ focal len of eye piece.*

To secure high magnification, the focal length of the obj glass is often made very great.

This, of course, causes the telescope itself to be of great leng since the latter has to be equal to that of the focal lengths object glass and eye piece added together. In 1722 Jam Bradley used an object glass with the enormous focal length of $212\frac{1}{4}$ ft.! The telescope had no tube, the object glass and eye piece being connected with a braced metal rod; but the practical difficulties must have been very great. These long, tubeless telesco were known as *aerial* telescopes.

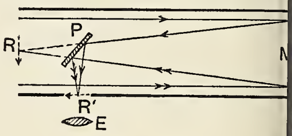


FIG. 26/12

Newton showed how to make a quite short telescope wh was as effective (or nearly as effective) as these very lo ones. It was known as a *reflecting telescope*, and the princi of it is illustrated in Fig. 26/12. The real image R inste

NEWTON'S REFLECTING TELESCOPE

Crown Copyright. From an exhibit in the Science Museum, South Kensington

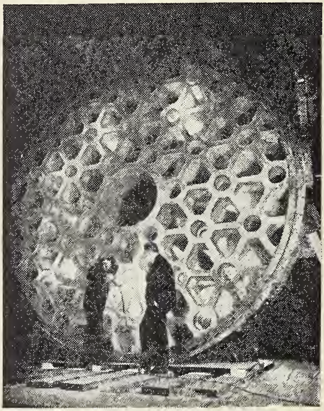
being formed by a convex lens, is formed by the concave rror M. The rays which would give rise to R are reflected by plane mirror P, and so the real image is formed at R′. re it is observed through the eye piece E as in the older m of instrument. A photograph of Newton's telescope ich is still preserved) is shown in the illustration. On the e of it is the inscription 'The first reflecting telescope ented bi Sr. Isaac Newton and made with his own hands he year 1671.'

ctually Newton was not, strictly speaking, the inventor his instrument. A man named James Gregory had worked the scheme about eight years before. But Gregory's ds were not as good as his head. He had no practical skill self, and could find no mechanic capable of working out ideas Newton was a skilled practical worker as well as eorist.

ewton's telescope was only about a foot long, but much ger instruments have since been constructed on very lar principles. In 1745, for instance, Lord Rosse (at sonstown in Ireland) completed one with a mirror 6 ft. ss, and with a tube 58 ft. long and 7 ft. in diameter. n Peacock once walked through it with his umbrella d up.) At the present time reflecting and refracting scopes are both in use, some being better for one purpose some for another. It may be of interest to give some iculars of one of the most modern instruments—a reflect- telescope which has been set up at the Mount Palomar rvatory in California. The mirror has a diameter of t., and although a 'ribbed' or honeycombed structure was oted to reduce weight, it weighs 20 tons. Something already been said (p. 137) of the difficulties connected the casting of such a mass of glass, and in fact, before ess was achieved, some 6 million dollars (say £$1\frac{1}{4}$ million ing) had been spent in unsuccessful attempts extending more than five years. The mirror was finally shaped paraboloid (cf. p. 242). The processes of grinding and hing were laborious in the extreme, occupying a team of ty-two men for four years. Their leader did not desist very square inch of the surface had been polished true ithin two millionths of an inch.

It is expected that with the help of this truly wonderf instrument, many hitherto unsolved problems of the univer will receive an answer.

We have said a good deal about refracting and reflecti instruments, but actually the very first telescopes ma were of quite a different type. The object glass consisted a convex lens as in the refracting telescope, but the eye pie consisted of a *concave* lens. The way in which an image w formed is shown in Fig. 26/13.



Mirror (17 ft. diam.) of Reflecting Telescope at Mount Palomar Observatory, California

By courtesy of The Corning Glass Works, U.S.A.

Rays from a distant object AB are indicated (A above axis, B on it), passing through the convex lens O. A r inverted image A′B′ would be formed, but before the r can come to a focus they strike the concave lens E. T causes them to diverge as shown, and a virtual image A″ is formed, erect in relation to the original object.

For a distant object, the distance from O to A′B′ wo of course, be equal to F_o, the focal length of O. The dista

n E to A′B′ is equal to its own focal length, F_e. Hence distance between the two lenses is $F_o - F_e$. In an ronomical refracting telescope the distance would, of rse, be $F_o + F_e$, so the 'Galileo' telescope, as it is called, sesses the advantage of *shortness*. A further advantage hat the image observed is *erect*. Hence we find that the ileo telescope, or rather a pair of such, is much used for ra glasses.

he invention of the Galileo telescope is surrounded by a ain amount of mystery. 350 or 400 years ago inventors e sometimes a little coy about announcing their dis- eries, for there was some danger that they would be

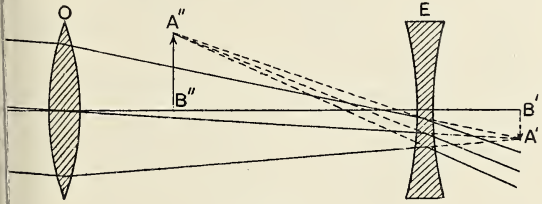


FIG. 26/13

ged with being in league with the Evil One. One account that the discovery was made accidentally by the children spectacle-maker playing with some lenses from the shop. showed their father the remarkable views they were ng, and he followed up the matter.

at may or may not be true. It is certain, however, that about 1570 onwards there were many rumours floating t of strange magnifying effects to be obtained by the f two lenses, and it is also certain that on October 2nd, Hans Lippershey, a maker of spectacles in Middleburg, nd, applied for a patent. Galileo heard rumours of the tion, and very quickly discovered for himself how to the necessary combination. Galileo, like Newton, was ful practical man as well as a great thinker, and before he had made an instrument which brought an object than thirty times nearer and magnified it nearly a and times.

Prismatic Binoculars. Going back for a moment to t astronomical telescope illustrated in Fig. 26/10, you c perhaps work out for yourself how, by using an additio convex lens, it is possible to obtain an erect image instead an inverted one. We then have a *terrestrial telescope.* disadvantage for common use is its length.

Prismatic binoculars, much used as field-glasses, are rea a pair of astronomical telescopes, in which the length greatly reduced by making the light pass through the tube three times. This is done by using two prisms, as shown in Fig. 26/14, arranged to give total reflection (p. 273). Notice that there are only two lenses (or lens systems), both convex, and so if it were not for the prisms the image would be invert both vertically and laterally. The first prism, resting on edge, corrects the vertical inversion, and the second, lying a triangular face, corrects the lateral.

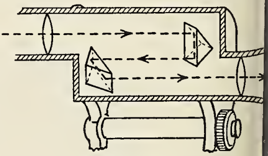


Fig. 26/14

The prismatic binocular shares with the Galileo telesc the advantage of shortness and compactness. In additi however, it has a wide field of view, which the Galileo telesc has not.

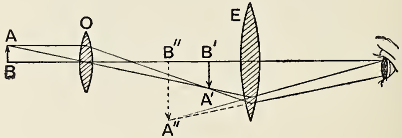


Fig. 26/15

The Compound Microscope. In this instrument the ob to be examined is placed just beyond the focus of the *ol* glass (or *objective*), the convex lens O (Fig. 26/15). This g us the real inverted image A′B′. E is the eye piece so pla as to be at a little less than its own focal length from A This gives us the virtual image A″B″, inverted with res to the original object.

'he image is, of course, much less bright than the original ect, because the same amount of light is spread over a h greater area. To make up for this loss of brightness, must be very strongly illuminated.

'o avoid distortion of the image, and colour effects, the ect glass consists not of a simple lens, but of a system of es very skilfully combined, and the same applies to the piece. The best modern microscopes will give magnifica- up to 2500 or 3000 diameters, but beyond this point the ge becomes too blurred for observation.

Questions

What sort of a lens is used as a simple magnifying glass? ain its action. Make a ray diagram to illustrate this use lens of 5 in. focal length, by a person who can see clearly object 10 in. (or further) from his eye. By measurement of liagram show that the magnification obtained is 3. *Lond.*

Describe with a ray diagram how two converging lenses may mbined to form a microscope.
converging lens of focal length 15 cm. is used to produce a mage of an object with threefold magnification. Calculate e the object must be placed.

Give ray diagrams to illustrate the action of a camera and re, and point out *two* similarities and *two* differences in their al arrangements. *C.W.B.**

The image of an object, 60 ft. away from the lens of a camera, duced on the screen 9 in. away from the lens. In what ion and through what distance must the screen be moved ler to receive a clear image of an object which is 10 ft. from amera lens? *C.W.B.**

Describe a simple photographic camera with a single ble lens, and explain how it works. The camera of a naisance aeroplane has a lens of 9 in. focal length. A re, enlarged 10 times from the original negative which was from a height of 10,000 ft., shows railway marshalling 27 in. long. What is the actual length of this target? *J.M.B.*

The eye contains a stop, a lens system, and a sensitive Draw a simple labelled diagram of an eye, showing the on of these three features. (*No other details are to be ed.*)
plain, with sketches, the two defects of the eye known as *ight* and *short sight* respectively. Describe the correction of these defects. *Camb.*

7. Why does one use convex lenses to correct long sight?

8. Explain the defect known as *short sight*, and show how may be corrected by the use of suitable spectacles. *Oxf.**

9. The 'near point' of a short-sighted person is 4 in. in fr of his eye, and he wishes to be able to read easily when a book at a distance of 1 foot. What kind of lenses will he need, a of what focal length?

10. An elderly man cannot read a newspaper when it is h nearer than 30 in. from his eye, and he wishes to be able to r it at a distance of 10 in. What kind of lenses, and of what f length, will be required?

11. Given two converging lenses of focal lengths 12 and 3 respectively, how would you arrange them to form a sim telescope? Illustrate your answer by a diagram showing h the image of a distant object is formed.

You would probably observe that when the instrument is u to view a white object the edge of the image is coloured. Acc for this. *Dur.*

12. For any *one* type of telescope, comprising two lenses o give the following information: (*a*) nature of eye lens (con or concave), (*b*) focal length of eye lens (long or short), (*c*) na of object glass (convex or concave), (*d*) focal length of ob glass (long or short), (*e*) appearance of image (erect or invert *J.M.B*

13. How can two lenses be arranged to form a compo microscope? State the sort of lenses used and their approxin focal lengths.

Draw a ray diagram in which at least two rays are tr through the microscope from a point on the object, not on axis, to the observer's eye. *Camb.*

14. The 2-in. objective of a microscope is replaced by on $\frac{1}{4}$-in. focal length. State (*without attempting any nume calculation*) what must be done to bring the image into f again, and what difference the exchange makes to the appear of the final image. *J.M.B.**

CHAPTER 27

COLOUR

our earlier studies of the subject of colour we saw that ·wton had found it a source of trouble, because when an ject was observed through a telescope of that period 1660) it was always seen surrounded by coloured fringes, d so the image was not sharply defined. This caused him make experiments on colour. In one of the most important them he made a hole about one-third of an inch in diameter the shutter of a room, through which he admitted a beam

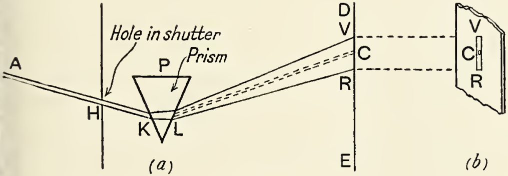


Fig. 27/1

sunlight. This passed through a prism, and was then ived on a screen, where it appeared as an oblong band of ur (Fig. 27/1). The experiment is more fully described pp. 260–1 of our earlier book. This separation of white t into its constituent colours[1] is known as *dispersion.*

was explained on p. 200 that the different colours corond to light of different wave-lengths, the red waves ing a length of about 0·8 micron (a micron = 0·001 mm.), the violet waves of about half as much. It was pointed too, that many wave-lengths are not represented in the *le* spectrum at all, some of them being longer than the red ra-red'), and others shorter than the violet ('ultra-violet'). ewton suspected that the coloured beams into which the

The seven colours of the rainbow,' which are red, orange, yellow, ı, blue, indigo, violet. The colours shade off from one to another; is no sharp transition.

X

light had been separated could not be further broken However, to make sure, he used a second prism and a sec screen, as shown in Fig. 27/2, which may be regarded Fig. 27/1 continued to the right. He made a small hole the screen so that light of a particular colour should p through (yellow, Y, is indicated in the figure), strike the sec prism and be refracted to the second screen. He did t successively with different colours, and in each case fo that there was no further separation.

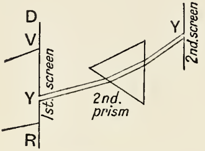


FIG. 27/2

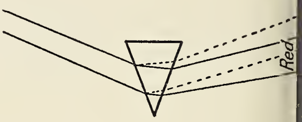


FIG. 27/3

The spectrum obtained as in Fig. 27/1 is *impure*—i.e. colours overlap. We can easily see how this overlapp arises. Although in the figure the yellow, for instance, the whole comes above the red, yet the yellow from the lo edge of the original sunbeam finishes below the red from upper edge (Fig. 27/3).

By using a smaller hole we shall have less overlappi but of course we lose a good deal of the light. To obtai *pure* spectrum we proceed as follows.

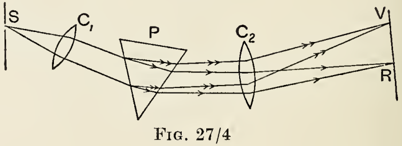


FIG. 27/4

S is a narrow slit, which may conveniently be cut i sheet of copper. To avoid the uncertainties of sunlight, may use artificial light—an arc-light for preference. slit is illuminated as brightly and evenly as possible, an lens C_1 is placed at a distance from it equal to its own f

ngth, so that the beam of light which emerges is parallel. his beam falls on a prism P, which is turned into the position f minimum deviation—i.e. the spectrum must be as near s possible to the patch of white light which would have ppeared on the screen in the absence of the prism. As the eam emerges it falls on a second convex lens C_2. In this ay the red rays are brought to a focus at R (on a suitably aced cardboard screen), the violet at V, and the other lours at points in between.

Instead of a solid glass prism, a hollow one filled with rbon disulphide is sometimes used. This results in the oduction of a much wider spectrum.

The spectrum consists of a number of sharply defined ages of the slit, side by side. Because the slit is narrow, e images are narrow, and there is no appreciable overpping. If we used a really wide slit—say half an inch—we ould see some of the red at one end and violet at the other. the middle, however, all the coloured images would overlap, combining to form white.

Let us sum up the best conditions for obtaining a real, re spectrum. They are

(i) a narrow slit, so that the coloured images of it will not overlap.

(ii) a prism to produce the necessary dispersion. It must be in the position of minimum deviation (strictly speaking, for the *central* portion of the spectrum).

iii) convex lenses suitably placed, the one to give a parallel beam, the other to bring each of the coloured beams to a focus on the screen.

t may be well at this stage to look back at our definition Index of Refraction, given on p. 267.

Ve can see now that it will vary according to the colour the light. Thus the index of refraction of water is higher violet light than for red. Our definition, in fact, should d something like this. 'The Index of Refraction of a stance, *for light of a specified wave-length*, is the ratio of sine of the angle of incidence to the sine of the angle of action when light of the specified wave-length passes from (or, strictly, vacuum) into the medium in question.'

Pure Virtual Spectrum. A pure *virtual* spectrum—one th cannot be received on a screen—is very easy to obtain. A we need do is to put a vertical edge of the prism parallel the slit. On looking through the prism we shall probab see our spectrum at once. We now turn the prism until the spectrum is as near as possible to the slit—i.e. until the prism is in the position of minimum deviation. A very bright pure spectrum is observed. Fig. 27/5 shows how it is formed. For clearness, only the rays giving rise to the red and violet portions have been drawn, the red in thick lines and the viol in thin ones.

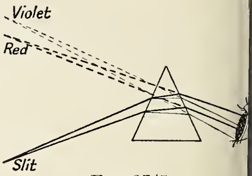


FIG. 27/5

If we look at a pin instead of the slit, the light reflect from the edge of the pin gives rise to coloured bands.

Recomposition of White Light. It appears from the for going experiments that white light is a mixture of lights different colours—the colours of the spectrum. By recombi ing these different colours we ought to obtain white ligl Newton easily showed that this could be done. Next to t first prism (Fig. 27/6) he placed a second similar one with edge turned in the opposite direction, so that the two formed a parallel plate with a narrow gap between the two halves. He now obtained a patch of white light on his screen. This experiment is closely connected with the fact th if a narrow beam of light is passed through a glass plate w parallel sides, the patch of light obtained on a screen at t other side is white. We may regard our glass plate as ma up of two prisms, one of them reversed with respect to t other.

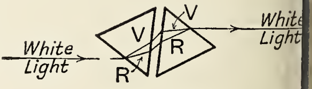


FIG. 27/6

Compound Colours. At this stage the reader will probal be under the impression that every colour corresponds light of a definite wave-length, 0·8 micron for red, for instan

is is by no means the case. There are many colours—own, for example—which are not in the spectrum at all. ;ain, suppose we cover half of a Newton's disc (*Junior ysics*, p. 262) with red paper and the other half with green. rotating the disc we obtain a *yellow*, which is practically e same as the yellow of the spectrum. The spectrum llow is *pure* (i.e. it corresponds to light of a definite wave-gth), while the 'red plus green' yellow is *compound*. Most the pure colours of the spectrum can be matched by a xture of other colours—the eye cannot tell the difference. means of a prism, however, we can tell easily enough. ppose, for instance, we wish to find whether a certain low is pure or compound. We observe a narrow strip of hrough the prism to get a virtual spectrum. If the colour compound, we shall see the component colours in the ctrum. If it is pure, we shall, of course, see only the single our.

bsorption of Colour. Suppose we put a piece of red glass he path of the white light that is giving rise to a spectrum—might put it in just to the right of S in Fig. 27/4. We now that all the spectrum disappears except the red part. dently, then, the red glass has absorbed all the light, ept the red. Similarly, a piece of blue glass absorbs all ept blue. If we put a red glass *and* a blue one in the path he light, the spectrum is completely blotted out, as we ıld expect. The red glass allows only red light to pass, this red light is absorbed by the blue glass.

/e might expect that a piece of yellow glass would blot every part of the spectrum except the yellow. Actually, ems to make very little difference, but on closer inspection ind that it has blotted out a part in the deep blue. The that reaches us through the glass is evidently not the pure ow of the spectrum, but a mixture of all the colours in spectrum except deep blue.

you go in for photography you will have noticed that colours seem to make too strong an impression on the —a blue dress or a blue flower often comes out white ie developed print. The trouble is that a photographic or film is unduly sensitive to the shorter wave-lengths to the blue–violet end of the spectrum). The difficulty

is removed by putting a transparent yellow 'screen' in fro of the lens. As we have already seen, this removes the de blue.

It was at one time thought that when light passes throu coloured glass, the colour was *added* to the light. We c see now that coloured glass acts not by addition, but subtraction. That is why, if a church contains a great ar of stained-glass windows, its interior will be dim.

Colour by Reflection. If we throw a spectrum on the scre as indicated in Fig. 27/4, and put a piece of red wool in vari parts of it, we find that it appears red in the red part of t spectrum, but black (or nearly so) everywhere else. R wool evidently reflects red light, but absorbs light of ev other colour. Similarly, grass is green because it absor every colour of light except green, which it reflects.

If, however, we put a primrose petal into different pa of the spectrum, we find that in the red part it appears r in the yellow part yellow, in the green part green, and so on. But in the deep blue it appears black. We are dealing with a compound colour, not a pure one, and if we look at it through a prism, we shall see a nearly complete spectrum—a series of images of the petal of every colour except blue. On the other hand, if we put some common salt int bunsen flame, to make it give the yellow 'sodium' flame, a look at this flame through a prism, we shall see a yel image *only*, because this particular yellow is 'pure.'

Red
Orange } B
Yellow
Green
Blue } A
Violet

FIG. 27/7

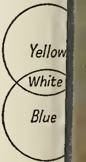


FIG. 27

While considering this particular colour, we may re the well-known fact that to obtain green a painter of mixes yellow and blue. The yellow pigment, like the primr petal mentioned above, absorbs the colours at the 'blue' of the spectrum (marked A in Fig. 27/7). The blue pigm absorbs the colours at the other end (marked B). Thus the light is absorbed except green, which is reflected.

But suppose you have two electric torches, each throw a white circle of light on a screen. Put a yellow glass in fr of one and a blue glass in front of the other. Our two cir on the screen are now yellow and blue respectively. M

e of the torches, so that the coloured circles partly overlap ig. 27/8). The result is not green, as you probably expected, t white!

The reason is that the yellow patch contained all the ectrum colours except blue (which was absorbed by the ss, cf. p. 311). When we added blue to this by moving e second torch, *all* the colours were assembled, giving white. e really *added* colours together, while in the case of the ie and yellow paints each pigment *subtracted* something, d between them they removed everything but green.

Many other little problems on colour present themselves daily life—and at examinations—and they are easily swered when once we have grasped the principles that we ve been discussing. We can see, for instance, that if we k at a Union Jack through a piece of red glass, the red will itinue to appear red, while the blue will appear black cause our red glass absorbs every colour of light except). The white part will, of course, appear red.

A room with blue wallpaper (or with walls distempered e) would seem rather dark if the electric light were covered h a rose-coloured shade. You can work this out for rself.

olours by artificial light. It should be clear by now that colour of an object depends on two things: (i) the light t it is capable of reflecting, (ii) the light that falls upon it. A te table-cloth is capable of reflecting all colours, and in a light would appear red, in a blue light, blue; and so on. ss is capable of reflecting only green, and in a red light ld appear black.

he fact that the colour of an object depends partly on the t falling upon it has important consequences in the match- of colours. Suppose a lady is unwise enough to buy a hat by artificial light, to 'go with' a red dress she has at ie. By daylight she will very likely find that though the s is red, the hat has undergone a mysterious change from to violet!

he explanation is that the proportion of red and blue is the same in electric light as in daylight. The electric t is relatively richer in red than daylight, or, what amounts ie same thing, it is poorer in blue. When the lady bought

the hat, it was reflecting red light and blue light, but n much blue, because there was not much of this colour prese On the whole, the hat seemed red. In daylight, howev the hat reflected a generous quantity of blue in addition the red, and the red plus blue gave purple.

Similarly, many a lady has complained that a dress wh was a rich blue by daylight has presented a very washed- appearance in the light of a ballroom. The dress-materia evidently capable of reflecting blue freely (absorbing ot colours). In the ballroom, however, the light is poor in b and so there is not much to be reflected. It is not very lik that sodium light (a pure, not compound, yellow), someti used for illuminating roads, will ever be used for lightin ballroom. If it were, everybody would appear to hav yellow face, and to be dressed either in yellow or in d mourning!

If you were asked whether you could suggest some me of altering the red : blue ratio in electric light, so as to m it nearer the ratio for daylight, you would very likely s 'I must either cut down the red, or increase the blue. I d see how I can very easily increase the blue, but I can down the red by making the light pass through a shade taining a suitable tint of blue. This blue would let thro the blue that is already there, but would absorb some of red.'

This is exactly what is done, and the result is 'dayl lighting'—a fair approximation to the balance of col found in daylight. Of course the amount of blue in the sh must be carefully adjusted. If it is too intense, it will ab all or nearly all the red, and the result may be worse than e More recently, fluorescent lighting has been used to pro the same effect.

Questions

1. Illustrate by means of a diagram the difference in the viation, as compared with the mean value for white light, of a red ray, (b) a blue ray, when passing through the same prism. ve reasons for your answer. *C.W.B.**

2. Explain why a pin when viewed through a glass prism, pears to be coloured. *Camb.**

3. Describe an experiment to show that white light can be it up into a number of coloured beams. How can these beams recombined, and what is the result of the recombination? How would you show that any one of the coloured beams nnot be further split up? *Dur.*

4. Describe how you would set up an experiment to throw a e spectrum on a screen. Draw a diagram to show the paths the rays which give rise to the red and blue colours in the ectrum.

What would be the effect on the spectrum of placing (*a*) a et of red glass, (*b*) a sheet of blue glass, and (*c*) a sheet of red ss and a sheet of blue glass in the path of the light?

What would be the effect of mixing some blue and some yellow ments? Give reasons. *C.W.B.*

. Explain why a grass lawn appears green when viewed ough a certain piece of glass whether the lawn is covered with w or not. *J.M.B.**

. What would be the appearance of a Union Jack if viewed cessively in red, blue and green light? Give reasons for your wer. *O.C.**

. Explain why a bright blue object, viewed by sodium light, ears to be black. *Camb.*

. A narrow strip of black paper is placed on a piece of white er. It is viewed through a prism with the refracting edge ermost and parallel to the strip. Describe and explain what would expect to see. *Dur.**

. If a man stands with his back to a lamp emitting white t and looks into a thick sheet of red glass held in front of him, sees two images of the light in the glass. Show, by diagram, these two images are formed and state the ways in which differ from one another.

he were to look through this sheet of glass at a white poster n red and blue letters on it, describe and explain what he ld see. *Lond.*

). Account for the appearance of a matt surface, which is (*a*) k, (*b*) white, (*c*) red, and (*d*) blue, when it is viewed in a beam ure red light. *Camb.**

l. The image of a brightly illuminated object produced on a e screen by a converging lens is often fringed with colour. at is the cause of this? Show clearly by a diagram what pens. *Dur.**

CHAPTER 28

SOUND—PRODUCTION AND PROPAGATION

Musical Sounds and Noises. Many sounds have a defin *pitch*; they are 'high' or 'low.' We think, for instance, of sound produced when a violin string is bowed, or a note the piano is struck, or the school bell is ringing. All s sounds are said to be *musical*. Many other sounds, howe have no definite pitch, as when somebody drops a he book on the floor, or bangs a door. On the whole, mus sounds are pleasant and noises are not, but there are ple of exceptions. The real distinction is that in one we hav note of definite pitch, and in the other we have not. concern is with musical sounds, though in the course of study we shall learn what a noise is, from a scientific p of view.

Sound produced by vibration. A little thought soon sati us that sound[1] is traceable to a certain kind of movem If we pluck a violin string to one side and then release i gives a musical sound, and at the same time it is mov rapidly from side to side, or 'vibrating,' to use the cor term. If we put our finger on the string for a moment, of course, stop the vibration—and at the same time we the sound.

We cannot see the separate vibrations because they too fast. By 'persistence of vision' the string seems to occ the whole space between its extreme positions. Very sim remarks apply to the effect produced by striking a tun fork. In many cases the vibrating substance is a colum air, as in the case of an organ pipe, or of wind instrum such as the cornet or trombone. A circular saw giv musical sound, which rises in pitch as the saw increases s and falls again as it slows down. In this case, as each t in succession strikes the wood, a quiver or vibration is se in the air, and it is the rapid succession of vibrations w gives the musical note.

[1] Here and afterwards *musical* sound will be understood unless is a statement to the contrary.

A medium necessary. In all the cases we have considered ; vibrating body is at some distance from the ear which :eives the sound, and between the two there is air. The estion at once arises, 'Could the sound be conveyed from ; vibrating body to the ear if there were no air in the space ;ween?' It was answered somewhere about 1650 by the rman Otto von Guericke of Magdeburg. Guericke had ented an air-pump, and this led him to try all sorts of cuum' experiments. In one of these he put a striking ck in a jar from which all the air was pumped out. The nd of the striking could then not be heard. The experint is often carried out to-day h apparatus very similar to ericke's, but an electric bell pended by a thin wire is usually ployed. The wires are connected ι Leclanché cell, which operates bell. As the air is pumped , the sound becomes fainter and ıter, until it cannot be heard ıll, though the clapper can be ı striking the bell. If now we

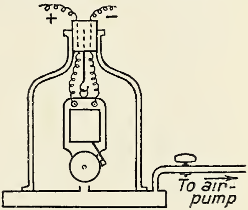


FIG. 28/1

) working the pump and open the tap to re-admit air, the ıd is once more heard. It seems clear, then, that sound ıot travel through a vacuum.

bservations on the sun lead to the same conclusion. ıg the telescope, men can see that mighty explosions are e often taking place—explosions so great as to blow out ece of the sun about the size of our earth and hurl it to a ance of perhaps a hundred thousand miles, after which it ɔs back. In comparison, the atomic bomb is almost ıing. Yet we never hear the faintest sound, because veen us and the sun, except for a hundred miles or so : the earth's surface, there is a vacuum.

ere, then, is one great difference between light and sound. ıt can travel through empty space; sound cannot.

ɔund can be conveyed by many other substances besides Any substance will do, solid, liquid or gas. If you are nming under water' in the baths you can hear the shouts eople outside, sound being conveyed through the water.

Then no doubt you have played 'telephones' (many y ago of course!) with two lids of cocoa-tins connected b stretched string. The sound is conveyed through the str A man may hear the sound of a very distant train by put his ear to the iron rails. Deaf people can sometimes hear sound of a watch by putting it between their teeth, the so in this case being conducted through the bones of the h Many modern appliances for the deaf depend on this princi

Pitch, Loudness and Quality. As sound is caused by vibrat we should expect that when sounds differ from one ano there will be some difference in the corresponding vibrati We must consider, then, the ways in which vibrations differ.

BA is one prong of a tuning-fork. If we knock the en on a table, the prong will start vibrating from one extr position BX to another BY. Considering the point A, vibrating between X and Y, we should say that AX or AY is the *amplitude* of its vibration—i.e. the amplitude is the distance from the position of rest (A) to the extreme position reached on either side (X or Y). The fork sets up vibrations in the air—a point we shall consider more fully presently—and a section of air, PP′, might vibrate between extreme posi MM′ and NN′. Here again PM or PN would be amplitude of vibration. In the case of a section of air to the fork the amplitude will be greater than for a se farther away. Also, the sound close to the fork is *l* than the sound farther away. This fact—i.e. that as amplitude falls off, so does the loudness—strongly sug that the loudness of a sound is connected with the ampli of the vibration which accompanies it. We can confirm conclusion in various ways. Thus if we tap the fork o table gently, so that the prongs move with a vibration of s amplitude, the sound is soft. The harder we tap the the greater must be the amplitude of the vibration o prongs, and (we know by experiment) the louder is the so

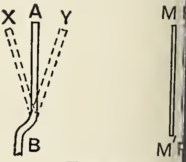


FIG. 28/2

But vibrations may differ not only in amplitude, they

er in *frequency*—i.e. in number per second. The prong ne tuning-fork may move to-and-fro much faster than the ng of another. In that case, of course, it makes more ations per second, and we say it has a *higher frequency*. question arises: In what way would a sound produced by ations of high frequency differ from one produced by ations of a lower frequency?

simple experiment will help us to answer the question. a long strip of steel AB, say 2 feet long, be clamped in a near the end B. Then push A nwards and release it. It vies up and down so slowly that an see the separate vibrations rhaps we can almost count n. No *note*, however, is prod; the vibrations are too .

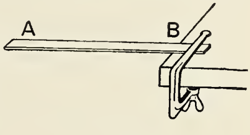


Fig. 28/3

ow move AB to the right and tighten the clamp again at the free portion of the steel is shorter. Push A downls once more and release it. We can see that it vibrates rapidly than before. Evidently the shorter we make ree portion of the steel, the more rapidly it vibrates.

ntinue to move B to the right. A certain point is reached we can detect a *note* of very low pitch. Then as we nue to shorten the free portion of the steel we notice we get notes of higher and higher pitch. Evidently, pitch is connected with frequency. *The greater the ency of vibration, the higher the pitch.*[1]

e same point may be proved in other ways. A circular of steel or cardboard has holes bored in it, equidistant one another[2] and from the circumference. A piece of

[1] ncidentally the experiment with the steel spring gives us very evidence that sound is caused by vibration. When the spring , we can *see* the vibrations. When it is short enough to produce , it is reasonable to suppose that it is still vibrating, besides there is the visible 'blurred' effect produced by persistence of .

[2] the notes are bored at irregular intervals we get an effect that nly be described as *noise*—a confused sound with no definite Thus we have a clue to the difference between a musical sound noise. The one is produced by a movement repeated at regular als (i.e. by true vibration), the other by a movement repeated gular intervals.

glass tubing T is held by a clamp so as to be at right an to the plane of the disc and directed at one of the holes. glass tubing is connected by rubber tubing either to a f bellows or to a supply of compressed air; or if neither of t is available, one may blow with the mouth.

The disc is now rotated either by turning a suitably pl handle, or preferably by a motor. As it rotates, a puf air passes through each time a hole comes opposite to T, the successive puffs set up successive vibrations. By tur the wheel faster we evidently increase the frequency of the vibrations, and as we do so we observe that the note rises in pitch. When we let the wheel slow down, the pitch of the note falls. The same point is illustrated yet again by a circular saw, where the vibrations are set up by the teeth striking successively against wood, as mentioned on p. 316. Here the pitch of the note rises as the saw is being started up, remains steady while it is rotating at cons speed, and falls when it is allowed to slow down.

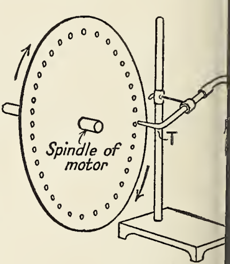


Fig. 28/4

We have now accounted for loudness and for pitch, first being dependent on the amplitude of the vibrat and the second on their frequency. But notes may in another way. Two notes, one sounded by an organ the other by a violin, may be equally loud and of the pitch—yet there is a difference. We say they diffe *quality*. You hear one man sing a song, and you say, ' a lovely voice!' A little later you hear another man the same song, and you hope there are not many more v Yet the two men may have sung perfectly in tune, and equal loudness. Again the difference is in the *quality* o notes.

The question we have to answer is this. If two note of the same loudness and pitch, but of different quality, difference is there in the corresponding vibrations? know the difference is *not* one of amplitude or of frequen

[T]he explanation lies in the fact that a given tone is rarely [sim]ple—i.e. it does not correspond to vibrations of one [fre]quency only, but of several. When, for instance, we sound [a n]ote on the piano, the octave and a number of other notes [are] produced at the same time. These extra notes are called [ove]*rtones*, the note originally sounded being called the *funda[men]tal.* In most instruments, the frequencies of the overtones [are] simple multiples of that of the fundamental.

[C]omparing, for instance, a note of the same pitch on a [viol]in and trumpet respectively, overtones will be present in [bot]h cases, but some which are weak in the case of the violin [not]e will be strong in the trumpet note, and vice versa; or [som]e may be present in one case and absent in another. The [ove]rtones of higher pitch are much more pronounced in the [case] of the trumpet, and it is this circumstance which gives [the tr]umpet note its ringing quality.

[W]e can obtain some confirmation of this explanation by [usi]ng two tuning-forks,[1] C and C′—i.e. upper C—each pro[vid]ed with its sounding-box. On sounding them together [we] obtain a rich, full note (C). If now we quench C′ by [touc]hing the fork with the fingers, we notice an immediate [cha]nge in the quality.

[Th]e *quality* of a note, then, depends on the particular [over]tones present, and on their strength.

[R]eproduction of Sound. Since all the features of a sound—[its] pitch, loudness and quality—are definitely related to [corr]esponding features of the vibration which produced it, [it f]ollows that if by some means we could reproduce the [vibr]ation, we should be able to reproduce the sound. We [shall] now see how this is achieved, contenting ourselves for [the m]ost part with general principles.

[Su]ppose AB (Fig. 28/5) is a sensitive diaphragm, connected [to] the bent lever CDE. This makes a right-angled bend [at D] and is pivoted at P. As C moves to the right, E will [mov]e to the left, and vice versa.

[Th]e arrows represent sound-waves, say from a speaker's [voic]e, impinging upon the diaphragm, and causing it to [vibr]ate. This causes corresponding vibrations of E, a needle [poin]t in which the lever terminates.

[1] A tuning fork gives a simple note—i.e. overtones are absent.

E is in contact with a waxed plate, revolving at a unif speed. As the plate revolves once, a circular channel produced by the needle, but the base of the channel show continuous wavy line owing to the vibration of E. As have described it, E would continue to make circular chan coinciding with the first, but by means of suitable mechan it actually traces a spiral, finishing near the centre of plate.

Suppose we are now able to make the waxed surface *hard*, and we replace the disc in the position of Fig. 2 We set it revolving once more. *Before*, vibrations of AB caused E to trace out a wavy path. *Now*, the hardened path, pressing against E, causes AB to repeat its original vibrations, and therefore to repeat the sound which produced them.

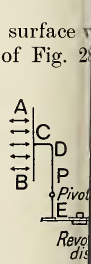


Fig. 28/5

There is rather a lot of 'supposing' about all this, yet in broad outline it indicates how sound is actually reproduced—i.e. (i) the waves produced by the vibrating body are made to produce movements in a needle, which in turn le a record of its movements in wax, and (ii) the process i versed, as already indicated.

The early records were actually traced out by an arra ment very similar to that represented in Fig. 28/5, b much superior electrical method is now employed, rather complicated for description here. It is, however, eas understand how the soft path in the wax is converted i hard one. The waxed surface is first 'metallised'—i.e. d over with a very fine metal powder to make it electri conducting. By electrolysis (Chap. 34), a thin layer of co is deposited over it, followed by one of nickel. The ni plated copper is now a negative or reversed copy of the ori It is separated from the waxed surface, and backed w steel plate to strengthen it.

Discs of a black, plastic mixture looking like vulc are now prepared, and these are placed in turn agains negative and subjected to very high pressure. When pressure is released and the black substance has coole have a perfect reproduction of the original, but in a

›stance instead of in soft wax. A single negative serves the preparation of some thousands of records.

Iow sound travels. We have already seen that sound not travel through empty space, though it travels readily ugh through air, water, iron—in fact through any material stance, whether solid, liquid or gas. *How* does it travel?

'hink of a line of railway trucks, A, B, C . . . Y, Z, with engine touching A (Fig. 28/6). The trucks are separated the usual spring buffers.

'he engine gives a sudden push towards A. What happens? 'he springs *a* are, of course, compressed, and A is pushed the right. This movement causes the springs *b* to be ıpressed, and B in turn moves to the right, and so on, finally the springs *z* are compressed, and Z moves to the t. In short, A, B, C . . . all move in succession to the t, and as the little spaces between the buffers close up,

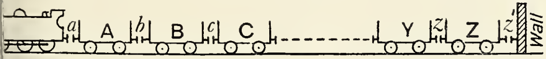


FIG. 28/6

hear a clank, clank, clank all down the line. We say a *wave of compression* is passing along.

ow, soon after this wave of compression has started— before it reaches Z—the engine, pushed by the comsed springs *a*, will spring back to the left. The springs e now relaxed, causing A to move sharply to the left, so on till the movement reaches Z. We hear another s of 'clanks' following the first series, and we say that a *of rarefaction* is passing down the line. In both cases ıpression and rarefaction) the *wave* moves from left to , but while in the case of the wave of compression each moves to the right—i.e. in the *same* direction as the —in the case of the wave of rarefaction each truck es to the left—i.e. in the *opposite* direction to the wave.

›w, instead of trucks A, B, C . . ., let us imagine the *air* led into sections A, B, C. . . . Instead of an engine moving enly to the right, let it be some vibrating body, say P, ›rong of a tuning-fork (Fig. 28/7). P will compress A,

A will compress B, and so on, and a wave of compressi passes through the air. Then P springs back, reducing t pressure on the left of A, and so A springs back, then B, a so on. Our wave of compression is followed by one of ra faction, and it is this double wave which forms a *wave sound.* After P has gone as far as it can to the left it w of course, start moving once more to the right, giving r to a second wave of compression. In fact, if we could what was happening, we should see a constant succession waves set up by the vibration of P, a compression ev time it moves to the right followed by a rarefaction every time it moves to the left. Evidently one complete vibration—i.e. one complete to-and-fro movement—gives rise to one complete sound-wave, made up of a wave of compression and one of rarefaction. A 'C' fork vibr 256 times per second. Such a fork will set up 256 compl sound-waves in one second.

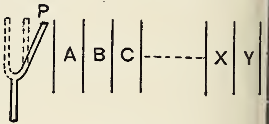


FIG. 28/7

For simplicity, the sections of air in the figure, A, B, C . are represented as all being in a straight line. Actu of course, a body vibrating in the air produces disturbanc round it, and this sound is heard in all directions, tho (usually) more in some directions than in others.

Wave-length. In our discussion of how a sound-wave trav we have spoken of a wave of compression reaching one sec of the air, while a following wave of rarefaction has reac another. We must *not* understand, however, that the in mediate sections are neither compressed nor rarefied. transitions are gradual, not sudden. If we represent sections of air by parallel lines, putting them closer toge or farther apart to indicate the degree of compressio rarefaction, we get a state of things somewhat as show Fig. 28/8*a*.

We are much more familiar with waves on the surfa water than with sound-waves. Fig. 28/8*b* represents a wave passing from left to right. It is really quite diffe from a sound-wave, because the material substance (in

e water) does not move in the direction of the wave, but right angles to it. Still, it may help us if we think of our nts of maximum condensation C_1, C_2, C_3 . . . as being nething like the crests of our water-wave, while the points R_2, R_3 . . . are something like the troughs.

Now, in a succession of water-waves (Fig. 28/8*b*) the wave-gth is the distance from crest to crest (e.g. from C_1 to C_2). ually, it is the distance from trough to trough (e.g. R_1 to , and there are many other distances that could be quoted— L_2 to L_3, where L_2 and L_3 are said to be in the same *phase*. vever, for convenience let us say the wave-length is the

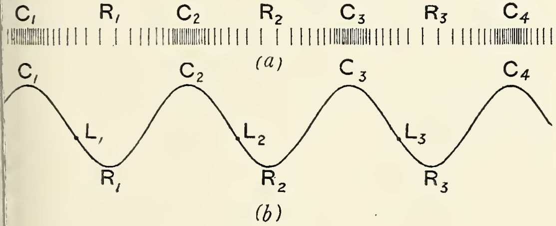


FIG. 28/8

ance from crest to crest. Similarly, the wave-length in case of sound is the distance from one point of maximum densation to the next (e.g. C_1 to C_2), measuring in the ction of the wave.

ext, suppose the body which is producing our sound-es—say the prong of a tuning-fork—is making n vibrations second. After one second has elapsed n waves will have sent out, and the total length of the train of waves will $\times\ l$, where l is the wave-length. But by this time—i.e. one second has elapsed—the first condensation will have elled a distance v, where v is the velocity of sound, and $= n \times l$, i.e. *velocity of sound = frequency × wave-length.*

mple. *Calculate the length of the waves sent out by a C tuning frequencing* 256), *taking the velocity of sound as* 1100 *ft. per sec.*
re $\qquad v = 1100$ and $n = 256$.

$$1100 = 256 \times l$$
$$l = 1100 \div 256 = \mathbf{4{\cdot}30\ ft.}$$

Velocity of Sound. We have just referred to the veloc of sound as 1100 ft.—roughly one-fifth of a mile—per This is, of course, extremely slow in comparison with velocity of light (186,000 miles per sec.). Let us first re a few observations which show that sound has a comparativ low velocity.

When walking along a country road you may have see stone-breaker at work some distance ahead. You see h hit the stone, but there is a perceptible interval before hear the sound. You *see* the action practically at the mom it occurs, because light travels at such an immense sp The little interval between seeing and hearing is the t taken by the sound to travel from the stone-breaker to y When you get within 30 or 40 yd. of him the interval is short that you cease to be able to detect it.

You can think of other examples for yourself. A v good one is the case of thunder and lightning—you see lightning before you hear the thunder. By observing interval you can make a rough estimate of your dist from the centre of disturbance. Suppose the interva 10 sec. Taking the velocity of sound as one-fifth of a per second, this gives a distance of $10 \times \frac{1}{5} = 2$ miles.

Let us now consider how the velocity of sound has determined.

One of the oldest methods, used about the year 164 the Jesuit Père Mersenne, was to get a man to fire a p at a known distance. Mersenne noted the interval betw seeing the flash and hearing the report, and easily worked the velocity. Thus if the distance were 4200 ft. and interval 3 sec., the distance travelled per second woul $4200 \div 3 = 1400$ ft.

Obvious sources of error are that: (i) the time interv so short than an error of, say, even one-tenth of a se makes a considerable difference to the result, and (ii allowance is made for the direction of the wind.

In 1738 several members of the French Académie Sciences who had recognised these sources of error used cannon, 18 miles apart, at points that we will call A an By carrying out the experiment in both directions (A and B to A), and taking the average of the two results,

ninated the wind effect. Further, with such a great tance the time interval was reasonably long, about 86 sec. tually, they obtained very good results.

3ut the velocity of sound may be found quite easily in the oratory, using simply a tuning-fork and a glass tube. The thod will be discussed later (p. 340).

Effect of temperature, pressure, etc. It was shown long ago Newton that the velocity of sound in a gas is proportional $\sqrt{\frac{P}{D}}$ when P is the pressure and D is the density. Now

(i) If we increase the temperature of a gas we reduce its density, and so we increase the velocity of sound.
The increase is actually about 2 ft. per sec. for each degree C. rise in temperature.

ii) If we increase the pressure P, we increase the density D in the same proportion, and the two 'cancel out.' Hence *change of pressure makes no difference to the velocity.*

ii) If we increase the *humidity* we exchange some of the air for water vapour, which is less dense. Hence we get *increased velocity.*

v) For a similar reason, the velocity of sound will be increased if for air we substitute a lighter gas such as coal gas, and vice versa (for expt. illustrating this, see p. 345).

v) Wind involves bodily movement of the air, and so the velocity of sound is greater in the direction of the wind.

) summarise, *the velocity of sound is independent of the sure, but increases with the temperature (about 2 ft. per sec. ach deg. C.); it increases with the humidity, and is greater light gas than in a heavy one. It is greater in the direction e wind than against it.*

termination of frequency. The lowest rate of vibration can give a note audible to the human ear is about 30 sec., the highest something like 30,000. How are iencies determined?

ere is one method, though it would not apply very well

in the extreme cases mentioned, because of the difficulty 'matching' the note.

The instrument used is a *disc siren.* It consists of a dru shaped metal wind-chest into which air can be blown fr bellows. In the top, at equal distances from one anot and lying along a circle, a number of holes are drilled, not vertically, but at an angle (see L in Fig. 28/9*b*, which shows the top disc in section). Resting on this fixed disc is a movable one similarly bored, but with the holes sloping in the opposite direction (U in Fig. 28/9*b*). When wind is blown into the chest, the air escaping through the fixed disc causes the movable one to revolve. Suppose there are 16 holes in each disc. Then in the course of one revolution the two sets of holes will coincide sixteen times, and at every coincidence there will be an escape of air from the chest. At ten revolutions per sec. (for instance) 16×10 or 160 puffs per sec. would escape f the chest, and we should get a *note* of frequency 160.

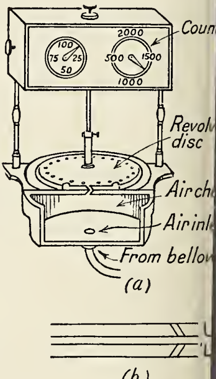


Fig. 28/9

The revolution of the upper disc operates a coun mechanism as shown, and the number is recorded somew as on a gas meter.

Suppose we wish to find the frequency of the note prod by any given source of sound (tuning-fork, organ pipe, e We set the dials to zero and (by moving a button) take that they are out of gear. Now we get a helper to k sounding (say) the fork, while we operate the bellows, blov harder or more gently until the note from the siren matches that from the fork. We now observe the t preferably on a stop-watch, and simultaneously put counting mechanism into gear. We keep as steadily possible to the right note for a measured time, at the en which we stop the mechanism.

Suppose the period was 20 seconds, and the dials indicate at in this period 360 revolutions have been made. The mber of holes in the disc, we will suppose, is 16. The mber of vibrations set up in the 360 revolutions is 16×360.

But these vibrations have been produced in 20 sec.

$\therefore$ number per sec. is $(16 \times 360) \div 20 = 288$

d so the frequency of the fork is 288.

Musical Intervals. While on the subject of frequency, it is eresting to notice that when sounds blend pleasantly into chord there is a simple ratio between their frequencies. us if we strike the notes C, E, G, C′ on the piano, we get familiar chord *Doh*, *Me*, *Soh*, *Doh′*. We could show that frequencies are in the simple ratio 4 : 5 : 6 : 8 by using disc siren to help us find the frequency of each note in n, when the results would be found to 'cancel' to the simple ios just given. A more direct method, if the apparatus vailable, is to use *avart's wheel.* In one form this we have four toothed eels mounted on the same e, the numbers of teeth ng in the ratio 4 : 5 : 6 : 8. actual numbers might for instance, 40, 50, 60, We set the apparatus notion (preferably with a or) aiming at a constant, lerate speed; and then we l a piece of cardboard lightly, and in rapid succession, inst the teeth of the four wheels. The intervals of *Doh* *Soh*, *Doh′* are very obvious.

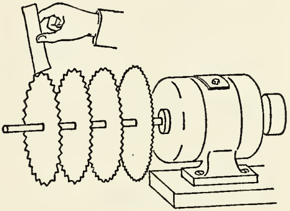


FIG. 28/10

he notes of the familiar *diatonic scale* (*doh*, *ray*, *me* . . . , or on the piano[1] C, D, E, F, G, A, B, C) have frequencies he ratio 24, 27, 30, 32, 36, 40, 45, 48.

C D E F G A B C

interval between two notes is represented by the ratio veen their frequencies, the higher one coming first. Thus

[1] The statement is not *quite* true for the piano, but sufficiently so ll practical purposes.

the interval between E and C is $\frac{5}{4}$ ($\frac{30}{24} = \frac{5}{4}$), while that betwe upper C and lower C is $\frac{2}{1}$. This particular interval is know as an *octave*.

Reflection of a Sound-wave. It is common knowledge th when sound-waves strike against an obstruction such as t wall of a quarry, they are reflected, giving an 'echo.' L us try to make out exactly what happens by referring ba to the 'engine-and-waggons' illustration of p. 323.

Suppose the wave of compression has reached Y. This pushed to the right, compressing the spring z, which caus Z to move to the right. This compresses the spring z'. N

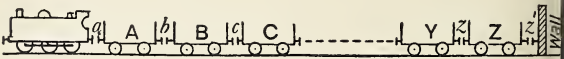


FIG. 28/11

z' cannot push the wall to the right, so being compressed, pushes against Z, making this move to the *left*. This co presses the spring z, which in turn causes Y to move to t left, and so on. Clearly the wave of compression which h travelled from A to Z is being reflected as a wave of co pression travelling from Z to A. You can trace out for you self the history of a wave of rarefaction which has travell from A to Z, and you will find that it is reflected as a wa of rarefaction.

Leaving our illustration now and going back to the 'r thing,' we see that on reaching an obstacle, a sound-wave reflected unchanged,[1] because the waves of compression a rarefaction of which it is made up are each reflect unchanged.

It will save trouble later if at this point we go back o more to our illustration, and consider what happens if last truck Z is *free*.

A wave of compression travelling from A reaches Y a pushes it to the right, compressing the spring z. This pus the truck Z, *which shoots an abnormally long distance to right because there is nothing to stop it.*

[1] I.e. unchanged in character. There is always, however, s weakening as the result of absorption, and the absorption may complete, as when sound waves strike a heavy curtain.

This sharp movement of Z to the right opens out the spring causing Y to move sharply to the right, and so on. The ve of compression which travelled from A to Z is being lected as a wave of rarefaction. Similarly we could work t the case of a wave of rarefaction travelling from A to Z— s reflected as a wave of compression travelling from Z to A. ese are the characteristics of reflection at a free end—com- ssion reflected as efaction and ra- ction reflected as npression.

So far we have said hing about the *le* of reflection. n the case of light angle of reflec- ı is equal to the le of incidence 229). When es- ishing this law had to use a ror, because the

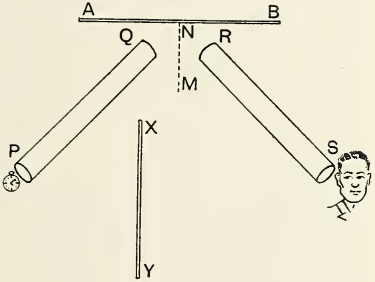


Fig. 28/12

e-length of light is so small (a few ten-thousandths of a imetre) that any little roughness would cause the light to hrown in some entirely different direction.

ound-waves are very much longer. Even the shortest can be heard have a wave-length of something like half ıch, and so for making experiments on reflection we do not l highly polished surfaces. A large sheet of iron or a kboard will do very well. In Fig. 28/12 AB represents a surface. PQ and RS are tubes of tinned iron, from 6 ft. long and about 3 in. in diameter. A watch is hung ıe end P of one tube, and the observer places his ear at end S of the other. A felt or baize screen XY is placed een P and S to prevent the hearer receiving sound-waves he direct path PS.

is found that the watch is heard best when the two tubes the normal are all in the same plane, and when the angle eflection is equal to the angle of incidence. Thus the of reflection are the same for sound as for light.

Echoes. We observe echoes most clearly when we sta at some distance, say 100 yd., from the perpendicular fa of a cliff or quarry, and give a handclap, or shout a syllal such as 'Bob.' The sound comes back to us perhaps h a second later. The sound-waves have travelled to the cli face, and have there been reflected in the way just explain If you are standing 275 ft. from the cliff, the sound-wa must travel there and back, i.e. *twice* 275 ft. (= 550 ft.) bef you will receive the echo. Now, it takes sound one seco to travel 1100 ft., so it will take half a second to travel 550

If you move close to the cliff, say to within 25 ft. of and shout, you will not hear an echo. The to-and-fro dista is now only 50 ft., and the time taken by sound to travel t distance is only 50 ÷ 1100 or $\frac{1}{22}$nd sec. In fact, the inter between your handclap and the echo is so short that y cannot perceive it—the two sounds are merged into o The shortest interval that most of us can detect is ab $\frac{1}{10}$th sec., and in this time sound can travel 110 ft. distance from the cliff-face would thus be 55 ft., and an e would be *just* perceptible. In foggy weather a ship steam in the neighbourhood of icebergs has often obtained v important information by means of echoes. The siren gi a short blast. Suppose the echo (from the nearest iceb is heard in 8 sec. In this time sound would travel 1100 × 8800 ft. But this is the to-and-fro distance, so the dista from the iceberg is 4400 ft.—about four-fifths of a mile. ship would, of course, proceed at greatly reduced speed, after a minute or so would use her siren again to see whe she was moving nearer to the iceberg or farther from it. the interval were now only 2 sec., for instance, the capt would no doubt give the order to reverse engines.

Echoes have sometimes been a great nuisance in a la lecture-hall. Every syllable heard is followed immedia by an echo, giving a confused effect, which makes it v difficult to hear what the speaker is saying. The diffic may be got over by hanging curtains, netting, etc., over walls, or even across the hall. These cause the sound to absorbed instead of reflected. Sometimes a hall which g troublesome echoes with a poor audience is quite satisfac with a good one—sound that would have been reflected f

By courtesy of The Submarine Signal Company (London), Ltd.

THE FATHOMETER FOR VISUAL ECHO SOUNDING

ıck arrows indicate electrical impulses. White rings and white arrows indicate sound waves.

an empty wooden seat is absorbed by the clothing of t
person sitting on it. In the same way you must have noti
how different a room 'sounds' when it is quite empty
carpets, etc., as compared with the same room when furnish
A sound in an empty room is reflected again and aga
striking perhaps wall, ceiling, floor, another wall and so o

Echoes applied to sounding. Countless ships have b
stranded or broken on a rocky shore because in darkness
fog they have not known how near they were to the sho
Hence from very early times it has been customary to t
soundings, usually with a piece of lead attached to a cord
wire, whenever there was uncertainty as to a ship's positi
There is an early record of such proceedings in Acts, ch.
v. 28.

The old method is still employed, but about 1920 a
better one, in which the essential feature is an echo from
sea-bottom, came into use. The 'fathometer' meth
represented pictorially on p. 333, works something like this

A loud sound is produced by the *oscillator*, a spring-driven plunger being made to strike against a steel diaphragm, the whole being suspended in water in a compartment adjacent to the ship's skin.

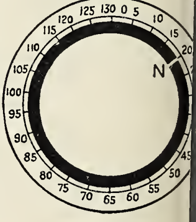


Fig. 28/13

The sound travels to the sea bottom, and the reflected wave is received by the *hydrophone*, mounted inside the ship's skin at a distance of about 45 ft. from the oscillator.

We must now notice the *indicator*. Here we observ
fixed circle graduated in fathoms. Just inside it is a revolv
circular band (shown black in Fig. 28/13), driven by a sn
constant-speed motor. A narrow radial slit N is cut ou
this band, and under it is a neon tube which flashes red w
it receives an electric impulse.

Just as the slit, in the course of its revolution, reaches
zero mark (0 in the figure) an electrical contact is set up wh
operates the oscillator and the plunger makes its sound.

When the hydrophone receives the echo, the vibratio
passed on to a simple two-valve amplifier, which conv

into an electrical impulse, and this lights up the neon lamp, d therefore the radial slit N. By this time N has, of course, velled some distance from the zero position, this distance pending on the time taken by the sound to make its double urney to the sea-bottom and back again. The dial *could* graduated in seconds, but it is obviously much more useful nowing the speed of sound in water) to work out the depth fathoms that corresponds to the true interval, and graduate dial accordingly. In the figure a depth of 20 fathoms ndicated.

More than twenty soundings a minute can be made by apparatus just described. Sometimes it is modified so to operate a pen which gives a continuous record of the th, rather like the barograph often seen in connection with ometers.

During recent years echo-sounding has been greatly de- oped. 'Ultrasonic' waves are now sent out, i.e. waves of h high frequency that the human ear cannot detect them. bottom of p. 327.) Since *vel. of sound = frequency* × *e-length*, and the frequency is very great, it follows that wave-length is very short. One great advantage of g such waves is that they can be reflected by comparatively ll objects—certainly by a large number of small objects, h as a shoal of fish. Since 1945, in fact, most vessels aged in the British herring fishery have carried echo- nders, which give great assistance in locating the shoals are seeking.

Questions

How would you show (*a*) that sound is due to vibration, hat a material medium is necessary for the transmission of d, (*c*) that sound travels with a definite velocity? *Dur.*

What are the physical differences between (*a*) a loud and a le sound, (*b*) a shrill and a deep sound?

lduce familiar evidence that sounds of all kinds travel at tically the same rate in air.

hat do you understand by the 'length' of a sound-wave? e length of a given sound-wave in air is 2 ft., what is the uency of vibration of the body producing it? (Velocity of d in air is 1100 ft. per sec.) *J.W.B.*

3. Describe the manner in which a sound-wave is produc and propagated through the air.

Show clearly how it is possible for musical notes of differe pitch and loudness to be reproduced by a vibrating diaphra *Camb.*

4. Describe some form of siren. Why does its operation le to the production of a musical sound? Explain how (*a*) t pitch, (*b*) the loudness of the note can be changed.

If the frequency of the note is 300 vibrations per sec. and t velocity of sound in air is 1100 ft. per sec., calculate the wa length of the sound waves produced. *J.M.B.*

5. What is meant by (*a*) resonance, (*b*) beats, (*c*) the qual of a musical note?

How are musical intervals defined? *Camb.*

6. Explain how an echo is produced and describe an experime which depends on echo formation, to find the velocity of sou in air.

A pistol shot is fired between two parallel high walls, 440 apart, at a point 110 yd. from one wall. Find the times of arri of the first four echoes at the firing point and give a diagr showing how the echoes are produced. (The velocity of sou in air is 1100 ft. per sec.) *Lond.*

7. A stationary ship sounds its hooter when near a cliff, an echo is heard 3 sec. later. Assuming that the velocity sound is 1100 ft. per sec., how far is the ship from the cl *J.M.B.*

8. Explain the formation of an *echo*.

A man stood facing a high brick wall 275 ft. away from h clapping regularly. He noticed that when he was just clapp ten times in 5 sec., each clap coincided with the echo of previous one. What value did he deduce for the velocity sound in air? *Camb.**

9. Explain fully:

(*a*) How 'fingering' a violin string alters the note produce

(*b*) Why the sound of your voice appears to be very loud w you are speaking in an empty room. *J.M.B.*

10. Explain the conditions required for an echo to be he A ship sounds its siren when it is 3850 ft. from a vertical c Taking the velocity of sound in air as 1100 ft. per sec., calcu how long it is before the echo is heard. At the moment of soun its siren a small depth-charge is exploded in the sea near the s and its echo from the undersea part of the same cliff is hear hydrophones on the ship after $1\frac{1}{7}$ sec. What is the velo of sound in water? Upon what factors does the velocity sound in air depend? *Lond.*

CHAPTER 29

RESONANCE

p. 327 it was mentioned that we could find the velocity ound in the laboratory by means of very simple apparatus. ore we can understand the experiment, however, we shall e to consider the subject of *resonance*.

uppose we take two forks of the same pitch (e.g. both C, frequency 256), each mounted on its sounding-box. We one of them strongly, and after a second or two quench vibration by pinching the prongs. It will be found that other fork is now sounding.

r remove the front of a piano so as to expose the strings. ss down the loud pedal and sing any single note into the rument. After you have stopped, the piano will be giving k the note you have sung.

o understand what is happening let us think of a person ng on a swing. Give him a gentle push, and later, another another, timing your pushes to agree with the natural od of oscillation of the swing. In this way the pushes are ed together, so to speak, and the swing is soon describing e a big arc. When you are 'working up' on a swing, you the movement of your body in the same sort of way.

metimes when walking across a plank over a brook you have found that it moves up and down rather alarmingly e period of your step happens to coincide with the natural od of oscillation of the plank. The remedy is obvious. iers are sometimes instructed to break step when crossing ht bridge to prevent a dangerous degree of oscillation.

ter an air-raid it was often thought advisable to remove e walls of houses, churches, etc., which had been left ding. One method was to pass a stout cable round the the other end being attached to an engine (Fig. 29/1). latter would then give a succession of tugs, timing them to coincide with the period in which the wall was swaying. r a few minutes the wall would come down.

w we can see what happens when you sing into the . One of the strings has a period of vibration cor-

responding to the note you sing, and the vibrations that y supply act upon it in exactly the same way as the tim impulses acted on the swing, or the plank, or wall. T phenomenon is known as *resonance*, and the string is said be set into *resonant vibration*. A similar explanation appl of course, in the case of the two tuning-forks.

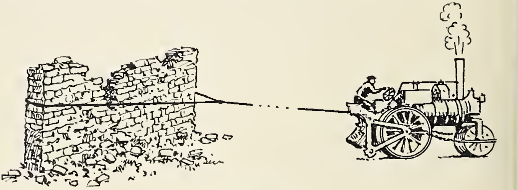


Fig. 29/1

Notice, too, that a tuning-fork does not give out m sound until we make its lower end touch a table or box. fork itself can set only a small quantity of air vibrat When it touches the box, however, the large wooden sur is set into 'sympathetic vibration' (as we often call vibra produced by resonance), and this in turn sets a large quan of air vibrating. Thus we obtain a much louder sound.

We can set a column of air into resonant vibration. T a tube about a yard long and an inch wide, closed at one end. Hold a vibrating tuning-fork over the open end. Probably the sound is very faint. Now pour in a small quantity of water and try again with the fork. Repeat the process again and again. You will find that when the water has reached a certain level the column of air resounds to the fork with a pronounced *hum* (Fig. 29/2).

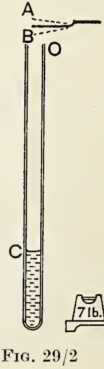


Fig. 29/2

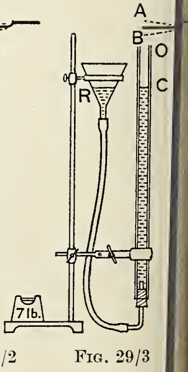


Fig. 29/3

In practice it will be found much easier to regulate the length of OC by using the

rangement shown in Fig. 29/3 and raising or lowering the servoir R.

Let us look a little more closely into the matter. In the gure, for clearness, only one prong of the fork is shown. In e position A it is just beginning to move downwards, sending wave of compression down the tube. This will be reflected the closed end C—the water surface—as a compression . 330), and when it reaches the open end O it will be reflected a rarefaction (p. 331).

Now, if at this moment the prong has reached the position (i.e. just about to begin its upward journey), it will itself sending a rarefaction down the tube, which will reinforce e rarefaction produced by reflection.

This rarefaction will be reflected at C as a rarefaction, and reaching the open end O will be reflected as a compression. this time the fork will have completed another half-bration, and will be back in the position A—just ready to nd another compression down the tube to reinforce the mpression produced by reflection. And so on. For onance, the condition is obviously this. The time taken a sound-wave to travel *twice* the length of the tube must respond to the time required by the fork to make half a bration, or we may say, while the fork is making one bration, sound must travel *four times* the length of the tube. But the distance sound travels while the fork is making vibration is the *wave-length* of the sound produced. For ve-length is the distance between two successive com-ssions such as C_2 and C_1 (Fig. 28/8*a* on p. 325), and a npression is produced with each vibration.

So if l is the length of the closed tube, which resounds to fork, the wave-length of the sound is $4l$.

By lowering the side tube, let us increase the length OC. sonance ceases, as we should expect. If, however, we tinue to increase OC until it is *three times* as long as it in the first resonance position, we secure resonance once re. Why?

uppose t is the period of vibration of the prong. It ved from A to B in $\frac{1}{2}t$ seconds, and because we had increased length OC, the return wave had not reached the open of the tube. But t seconds later—i.e. $1\frac{1}{2}t$ seconds after

leaving A—the prong is in position B again. The retu wave will have just arrived—it has had three times as lon journey as in the first case considered, but it has had th times as long ($1\frac{1}{2}t$ seconds instead of $\frac{1}{2}t$) in which to do and so we shall obtain resonance. Similarly, we sho obtain it if the length OC were made $5l$, $7l$ . . . where the shortest length that gives resonance.

Now let us see how we can use our tube and fork to f the velocity of sound in air. We must know the freque of the fork (we saw on p. 327 how this could be found, we may make use of the number stamped on the for Suppose it is 160, and that the shortest value of OC for wh the tube will resound is 20·6 in.[1]

The fork makes one vibration in 1/160th sec., or hal vibration in 1/320th sec., and in this time sound travels tw the length of the air column—i.e. $2 \times 20{\cdot}6$ or 41·2 in. problem then is simply this. If sound travels 41·2 in. 1/320th sec., how far will it travel in a second?

Clearly it will travel $41{\cdot}2 \times 320$ in., which works out 1099 ft.

By a similar experiment we could find the velocity sound in any other gas, by simply filling the tube with the in question. If the gas is lighter than air (e.g. coal gas) will obviously be necessary to have the closed end of the t upwards.

In the calculation just given the frequency of the fork known, and we were able to find the velocity of so Conversely, if the velocity of sound is assumed, we can the frequency of the fork.

Example. *A tuning-fork is sounded in a tube of* 1 *in. diam the length of the air column being adjustable by means of w The shortest air column for which resonance can be obtaine* 12·8 *in. Calculate the frequency of the fork.*

The velocity of sound at the temperature of the room (15° *C.*) *be taken as* 1120 *ft. per sec.*

[1] Actually it is found that reflection does not take place *exact* the open end of the tube, but a little way above it; and in accu work a length equal to $0{\cdot}3d$ would be added to our 20·6 in., d the diameter of the tube.

In calculations, *if d is given*, it is an indication that $0{\cdot}3d$ is t added as in the example which follows almost immediately.

Let n be the required frequency.

Then the time of one vibration is $\frac{1}{n}$ sec. and of half a vibration $\frac{1}{2n}$ sec.

In $\frac{1}{2n}$ sec. the sound travels twice the length of the tube, which llowing for the 'end correction') we must take as $12{\cdot}8 + 0{\cdot}3 =$ ·1 in.; so in $\frac{1}{2n}$ sec. sound travels 26·2 in.

But also, in $\frac{1}{2n}$ sec. sound travels $\frac{1120}{2n}$ ft.

or $$\frac{1120 \times 12}{2n} \text{ in.}$$

$$\therefore \quad \frac{1120 \times 12}{2n} = 26{\cdot}2$$

$$\therefore \quad 2n \times 26{\cdot}2 = 1120 \times 12.$$

ich gives $$n = \mathbf{256}.$$

Resonance from open tube. Suppose we hold a tuning-fork er an *open* tube. The prong is at A, beginning to move wnwards and sending a compression down the tube (Fig. 4). At the open end O′ the condensation is reflected as arefaction, which on reaching O is reflected again as a ndensation. For resonance, the prong must now be in ition A once more—i.e. the length of the tube must be h that sound can make the to-and-fro journey in the time one vibration. In the case of the closed tube it had to ke the to-and-fro journey in the time of *half* a vibration. dently, then, the shortest[1] open tube that will produce onance with a given fork is twice as long as the shortest sed tube.

The air inside the tube. When a tube, open or closed, is ounding, there are evidently waves travelling down the e at the same time that reflected waves are travelling he opposite direction. The air is said to be in a condition *stationary undulation.* Without attempting a detailed lanation of what happens, we may give a brief statement he consequences of this double movement.

[1] 'Shortest,' because obviously we could obtain resonance by making tube twice, three times, etc., as long, the reasoning being similar hat already given for a closed tube.

At certain points N_1, N_2, N_3 . . ., spaced at equal interva (Fig. 29/5*a*), the air is *still*. That is because at these poin it would be moving in one direction owing to the direct wav and in the opposite direction owing to the reflected one, t net result being that it does not move at all. These poin of no movement are called *nodes*.

Half-way between these there are points A_1, A_2, A_3 . . where the air has maximum movement. These points a known as *antinodes*. There is always an antinode at an open end, and always a node at a closed end. The distance from a node to an antinode is equal to one-quarter of a wave-length.

Fig. 29/4

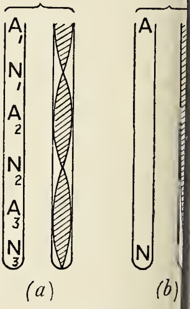


Fig. 29/5

A very simple case occurs when we are finding the velocity of sound by measuring the shortest closed tube for which resonance occurs (p. 339). There the air column AN (Fig. 29/5*b*) has only one node (at N) and one antinode (at Thus the wave-length = 4 × AN, and the velocity of sou is found by multiplying this length by the frequency of fork.

A common method of representing stationary undulat is by a pair of lines opening out to a maximum at an antin and intersecting at a node. The method will be clear fr the figure.

Note produced by blowing. Most boys know that by blow across the mouth of a test-tube a note of definite mus pitch is produced (though science masters are often singul unappreciative). Let us modify the experiment a little.

Take a piece of tubing about 9 in. × $\frac{3}{4}$ in. If be cutting it off it has been slightly drawn out at one end Fig. 29/6), so much the better. Fit it with a rubber stop mounted on a wire. This must be close-fitting, but no tight that it cannot be drawn in and out.

Now sound an 'upper C' fork above P and adjust the opper until resonance is obtained. Next, simply *blow* ross P.

The same note is obtained. This result is found to be neral—i.e. a tube or pipe gives out the same note when blown ross as it does when used to give resonance with a tuning rk.

Actually the blowing *is* producing resonance, though at st it is not obvious how the blast of air can act like the ning-fork previously discussed.

Suppose it is acting in the direction AB (Fig. 29/7). This produces a compression which travels down the tube, and, after being reflected from the bottom, travels up again. When it reaches the mouth of the tube

(i) It pushes the layer of air at AB into the position AB′—i.e. it changes the direction of the blast. This movement causes a *rarefaction* to start down the tube, just as would a similar movement of the prong of a tuning fork.

(ii) It is itself reflected as a rarefaction, which combines with the rarefaction produced in (i).

. 29/6

Fig. 29/7

Thus the blast acts for practical purposes like the prong ı tuning-fork. The difference is that the latter is so strong o have an *independent* movement, while the movement of blast of air is controlled by the returning compressions rarefactions.

The *frequency* with which the air at AB vibrates—and refore the note given out—depends, of course, on the gth of the air column, which can be altered by adjusting cork, or (using a test-tube) by pouring in more or less er. Using this principle, take a rack of, say, twelve testes (Fig. 29/8) and make the middle eight give the notes *ray, me . . . doh′*. The other test-tubes will enable to go two notes above *doh′* and two below *doh*. With

a little practice you will be able to give remarkable renderin of 'God Save the King,' 'Poor Old Joe,' etc.

Let us carry out a few more experiments with the tube Fig. 29/6. (We shall get better results if we do our blowi through a piece of tubing of about $\frac{1}{2}$ in. diameter, somewh flattened at the end, Fig. 29/9.)

Close the end Q with your thumb, and blow across P. N repeat, but with Q open. The second note is an octa higher than the first—i.e. it has twice the frequency. T agrees with the conclusion reached on p. 341, where we s

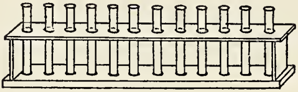


FIG. 29/8

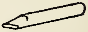


FIG. 29/9

that the 'closed tube' note has a wave-length of $4l$, while t open tube gave a note of wave-length $2l$.

Now frequency $\times$ wave-length $=$ velocity of sound (p. 3

$$\therefore \qquad \text{frequency} = \frac{1100 \text{ ft. per sec.}}{\text{wave-length (in feet)}};$$

so the 'open tube' note, having only half the wave-length the other, will have twice the frequency—i.e. it will be octave higher.

Overtones. Using the open tube, blow first gently, and t harder. The first note you get—the lowest it can give called the *fundamental*, say *doh*. On blowing harder you the octave *doh'*, and blowing harder still you may get s and then even *doh''*. If n is the frequency of the fundamen these higher notes have frequencies $2n$ (*doh'*), $3n$ (*soh'*) and (*doh''*). And if we could blow hard enough we should ob notes of frequencies $5n$, $6n$, etc. Such notes are the *overt* mentioned on p. 321.

Now repeat the work with the closed pipe. Calling lowest note—i.e. the fundamental—*doh*, we find that inst of our series being *doh, doh', soh' doh'' me''* . . . as with open pipe, we obtain *doh, soh' me''* . . . (probably you

›t be able to blow hard enough to obtain *me''*). If n is the equency of the fundamental, these overtones have frequencies ʹ $3n$, $5n$. . . .

Any note whose frequency is a whole number times n is ıown as a harmonic. Thus with an open pipe it is possible obtain *all* the harmonics as overtones, but with a closed pe only the odd harmonics.

Organ-pipes. Fig. 29/10 shows the essential features of an gan-pipe. It may be made of wood or metal. Air from e *wind-chest* rushes through the narrow opening O and ikes the lip L. Essentially this is like blowing across the ›uth of a tube. The pipe produces its fundamental note, d sounding along with this, but not so strongly, the overtones. The pipe may be open or sed, and in the latter case, of course, the overtes are limited to the odd harmonics. The quality the note depends on the overtones present and their relative strength. An open pipe gives a ıer note than a closed one because of the ater number of overtones present.

FIG. 29/10

)ther wind instruments. The principle that sical notes may be produced by vibrations set in a column of air is, of course, the essential ture of wind instruments. We will glance efly at a few of them.

n some, such as the fife and flute, the player ws across a column of air, which in some inıments—e.g. the flute, 'tin whistle'—is open, others—e.g. an ordinary whistle[1]—closed. To ain a higher note the player shortens the column of air by ning a hole in the side of it, a process equivalent to cutting the column at that point.

Mr. J. Goodier (Science Masters' Book, *Physics*, Series II) shows a whistle may be used to show that the velocity of sound in coalis greater than in air. 'A whistle is attached by a fairly long piece ıbber tubing to a gas tap. The gas is turned on and the whistle ıds its normal note, due to the air in the tube being driven through. note then rises sharply as the coal gas comes along.'

'he higher note, of course, indicates greater frequencies, and so sound waves must be making their little to-and-fro journeys more kly when the whistle is filled with coal gas, than when it is filled air.)

In the clarinet the air column is nearly closed by a flexil cane reed (Fig. 29/11). As it vibrates the column is alter ately opened and closed, a little puff of air being admitt to the pipe each time it opens, and producing resonance, mu as in the case of the organ-pipe. As the reed is not very rig its rate of vibration is determined chiefly by the rate at whi pulses travel up and down the pipe. Partly, too, its rate controlled by the player's lips, and to some slight degree its own rigidity.

A clarinet player can 'tune up' to some extent. He do it by slightly pulling out, or pushing closer together, the sections of his instrument. He thus gets a longer or shorter air column, and consequently a lower or higher pitch. You may have noticed, too, that an inexperienced player on the clarinet can produce overtones all too easily.

Fig. 29

The oboe, bassoon and saxophone have mouthpieces very similar to that of the clarinet.

In the bugle, cornet and a number of other instruments, the vibrating lips of the performer take the place of a reed, the rate of vibration being controlled by the rate at which pulses travel throu the column of air. In the cornet the player is constan altering the length of this by means of keys. In the bu there are no keys, and the player makes all his calls by me of overtones.

The mouth-organ strictly has no place here, because does not work on the 'column-of-air' principle. The reed rigid enough to have an independent rate of vibration— it is not controlled by the pulses in a column of air. The air supplied by the player escapes in a succession of little puffs, the frequency, and therefore the pitch, depending on the rate of vibration of the reed (Fig. 29/12). In fact the action somewhat sembles that of the disc siren. The 'rigid-reed' principl also used in the accordeon and harmonium. An organ also have 'reed pipes,' as distinct from 'flue pipes.'

Fig. 29/12

Questions

1. Explain carefully what is meant by resonance.
Describe how you would arrange a state of resonance between olumn of air and a given tuning-fork, and explain how you uld use the arrangement to enable you to determine the locity of sound in the air, the frequency of the fork being own. *J.M.B.*

2. A vibrating tuning-fork labelled 400 was held close over the of a glass tube, closed at the lower end, while water was ured in. When the level of the water was 21 cm. below the of the tube the note of the tuning-fork swelled out, but died ay again when more water was added. Explain this and w an important numerical conclusion from the experiment. *Lond.*

3. How does the velocity of sound depend on (*a*) the atmospheric ssure, (*b*) the temperature?

. If you were provided with a test-tube rack and a dozen ilar test-tubes, how would you use these to make a simple sical instrument? If the test-tubes were tuned to give contive notes of an ordinary musical scale (eight notes to the ave), and if the third test-tube from one end were tuned to ddle C, what would be the frequencies of the fifth, seventh tenth tubes? What relation would exist between the wavegths of the notes emitted by the third and tenth tubes? ddle C = 256. *Lond.*

. A tuning-fork of frequency 330 per sec. is held vibrating ve the open mouth of a tube about 1 metre deep, while water lowly sent into the tube through an inlet at the bottom. A l note is heard when the length of the air column above the er is 74 cm., and as more water is introduced the sound dies y, returning at full strength when the length of the air column educed to 24 cm. Explain why this happens, and calculate the ocity of sound in air from these observations. *J.M.B.*

CHAPTER 30

STRETCHED STRINGS

A GREAT many of the musical instruments we see arou us consist essentially of stretched strings; the violin, pi and harp are examples.

Stringed instruments, most commonly the harp, are of mentioned in the Bible. There is a list of instruments sev times repeated in the third chapter of Daniel, 'the soun the cornet, flute, harp, sackbut, psaltery, dulcimer, and kinds of musick.' Of these six, at least three, and possi four, were stringed instruments. But there are very m earlier records of stringed instruments. The illustration i reproduction of an ancient Egyptian drawing showing several varieties of harp. Notice the two on the right — remarkably like bows, but with a number of strings instead of the usual one. It has been suggested that the first musical sound to arrest the fancy of early man was the twang of his own bow-strings. Perhaps at the end of the day three or four of these primitive hunters would sit in t cave or hut obtaining different notes by twanging t different bows. Then one bright fellow thought of stretc another string across, so obtaining a two-note instrume and the step from that to the crude form of harp seen in old drawing would not be a very great one.

By courtesy of 'Encyc.

ANCIENT EGYPTIAN HARPS

At a very early date, too, man must have gained s rough idea of the laws of strings which we shall study in present chapter. He would find, for instance, that i increased the tension on his bow-string, he obtained a of higher pitch, and that this also happened if he excha

thick bow-string for a thinner one. Later his knowledge uld become more exact, and the Greek Pythagoras, who ed about 500 B.C., is known to have discovered that if a ing is divided into two lengths, then the simpler the ratio ween these lengths, the more perfect is the harmony ween the notes given out by the two parts.

Transverse Waves. Let us begin by recalling the kind of ve produced when you throw a small pebble into a calm nd. Just where the pebble enters, the water rocks up and vn (strictly speaking, first down, then up). This movent is passed on to the next portion (a small circular belt), n to the next, and so on. The *disturbance* or *wave* moves y rapidly towards the edge of the pond. The *water* moves y up and down—not sideways—as you can see by watching it of floating wood or cork. Such a wave—i.e. one in ch the material, in this case water, is moving at right les to the direction of the wave—is said to be *transverse.*

hat is the kind of wave that ses along a stretched string wire when you pull it to one and then release it. The e travels *along* the wire. h portion of the material, in succession, moves *at right es* to the length.

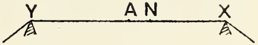


FIG. 30/1

uppose our wire is stretched between two fixed points nd Y (e.g. a violin string, stretched between the tuning and the bridge). When the wave reaches Y it is *reflected*, a moment afterwards it is reflected again from X, and n. Thus waves are passing *in both directions* along XY, as a few pages back we were considering sound-waves ing in both directions along a tube or pipe.

may happen that a point A which is just being pushed ards because of the right-to-left wave is also being pushed ards by the left-to-right wave. As a result we get a ially high crest, while next to it there will be a specially trough. On the other hand, there will be points, such , which are stationary, because the right-to-left wave and left-to-right wave are trying to move them in opposite tions, and simply cancel one another out.

ithout going fully into detail, it is important to notice

the general result. Fig. 30/2 shows the actual movement a portion of the wire as the two waves each advance a distan of one wave-length, the one to the left, the other to the rig We notice that certain points, N_1, N_2 . . ., spaced at regu intervals, are stationary. These points are called *no* Midway between these are points of maximum movem (A_1, A_2, etc.), where the crests and troughs are strong marked. These are *antinodes*. It is found that the distan between two successive nodes (or between two success

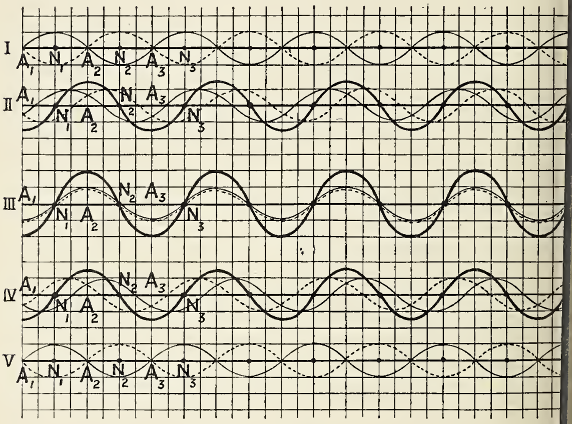


Fig. 30/2

antinodes) is equal to half a wave-length. It follows that e distance from a node to the nearest antinode is a quarte f a wave-length.

The wave-motion just discussed is known as *statio* *undulation*, because the nodes and antinodes, for insta , are fixed in position. Do not confuse transverse waves d stationary undulation. A transverse wave is *progressi* - the crests and troughs are continually advancing, as we when the pebble has just been thrown into the p d. Stationary undulation is the effect produced by the 'in ference' of two transverse waves, one direct, the other

ted. You sometimes see a good illustration near a pier promenade, where the reflected waves meet the waves still ing in. A small boat is rocked up and down very violently happens to be at an antinode.

he presence of nodes and antinodes in a vibrating string

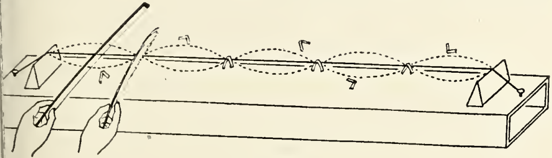


FIG. 30/3

wire may be shown by an interesting experiment first ied out by two Oxford scientists in 1676. A number of er riders are placed over the wire. The latter is then made ibrate by means of a bow, and is simultaneously touched a feather at an exact fraction of its length (one-fifth in 30/3) from one end. The point touched, being unable

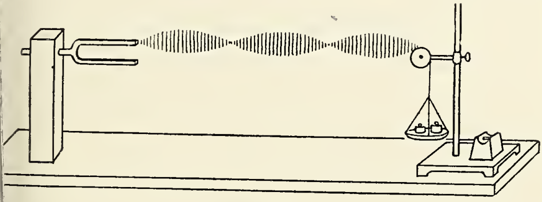


FIG. 30/4

ove, becomes a node. Other nodes are formed at equal vals, shown by the fact that at these points the paper s keep their places, but are thrown off everywhere else.

the experiment just described the vibrations, of course, die away, because we have made no arrangements for *orcing* the waves as they are reflected from one end or other. This reinforcement is secured in what is known elde's experiment. The string is attached at one end to ge tuning-fork of frequency 100 or less, while the other

passes over a pulley and is stretched by a weight (Fig. 30 The fork is made to vibrate by first squeezing the pro and then releasing them. The pulley is then moved a until a position is found in which the string vibrates in loop. On reducing the stretching force to one-qua (keeping pulley and fork in the same positions) the string be found to vibrate in two loops, and if the force is reduced to one-ninth it will vibrate in three.

Fig. 3

Laws of strings. In our earlier studies (*Junior Physics*, pp. 283–6) we saw that the frequency of vibration of a string depends on (i) its length, (ii) the force with which it is stretched, and (iii) the mass of unit length. We must now go into the subject more exactly.

In carrying out our experiments we shall use a *sonometer*. In its usual form this consists of two strings stretched across bridges, which are mounted on a long, rectangular wooden box (the box, of course, acting as a sounding-board). The best results are obtained if the box is hung against a wall (Fig. 30/5), the lower portion being made to project an inch or so.

An iron hook, on to which weights can be slotted, is firmly attached to the lower end of the string.

Frequency and length. Sufficient weights are placed on F to make AB when plucked give a clear rather low note. CD, which is simply a 'reference strin tuned to the same note by turning the tuning peg (not sho Call this note *Doh*.

A movable bridge G[1] is now placed under AB, and m until the length AG when plucked gives *Doh′*, the o above the reference note sounded by CD. It will be f that $AG = \frac{1}{2}AB$. Thus when the length is *halved* frequency is doubled.

Let us experiment a little further. We shall assume

[1] G must, of course, be of sufficient height to press agains string—but only just; if it pushes AB up appreciably it will in the tension, and this should be constant.

relative frequencies of *doh, me, soh, doh′* are as 4 : 5 : 6 : 8. his can be proved to be the case by finding the four fre- ncies by means of the disc siren—the experiment is cribed on p. 328—or by the 'Savart's wheel' experiment, 329.)

3y moving the bridge, find the length that gives *me*, and n the length that gives *soh*. We may set out our results this.

Note	Doh	Me	Soh	Doh′
equency	$4n$*	$5n$	$6n$	$8n$
ngth (cm.) . . .	100	80	66·7	50
oduct, frequency × length	$400n$	$400n$	$400n$	$400n$

Thus if the reference string is sounding C (frequency 256), $n = 64$, the actual value of n does not matter.

he law now stands out clearly enough. If a string is under constant tension, the product of frequency times th will be a constant; or, as it is more usually expressed, *string is kept under constant tension, its frequency of ition will be inversely proportional to its length.*

n alternative method is to use several tuning-forks of wn frequency, say 256, 320, 384, 512. The tension on is adjusted so as to make it give the lowest note required his case frequency 256), and then, keeping the tension tant, the length is altered so as to make the string give iccession the notes agreeing with those of the other forks. his case we should have no need of a reference string. results are set out as above, but of course n does not appear. is worth noting that the law just established gives us an method of comparing the frequencies of two tuning- . We adjust the bridge until the wire is in tune with rst fork (frequency n_1), and measure the length, l_1, between bridges. We do the same for the second fork (frequency If the length is now l_2, then $\frac{n_1}{n_2} = \frac{l_2}{l_1}$.

equency and Tension. We begin as before, AB giving note and CD being in tune with it. This time, however, iall need to know the weight of the iron support. Suppose

this is 0·8 kilos, and that the weight slotted on to it is 2 kil total 2·8.

We now put on extra weights until AB is sounding octave. Suppose the attached weights are now 10·4 ki Adding 0·8 for the weight of the support, we have a tota $10{\cdot}4 + 0{\cdot}8 = 11{\cdot}2$. Now 11·2 is just *four times* 2·8. T to double the frequency we have had to increase the ten fourfold.

It looks as though the frequency is proportional to *square root* of the stretching force. To test this, we find w tension is required to make the string sound *me*, and af wards *soh*. With careful work, such results as the follov would be obtained.

Note	Doh	Me	Soh	Doh'
Frequency . .	$4n$	$5n$	$6n$	$8n$
Stretching force .	$0{\cdot}8 + 2{\cdot}0 = 2{\cdot}8$	$0{\cdot}8 + 3{\cdot}6 = 4{\cdot}4$	$0{\cdot}8 + 5{\cdot}5 = 6{\cdot}3$	$0{\cdot}8 + 1$ $= 11{\cdot}$
$\dfrac{\text{Frequency}}{\sqrt{\text{Stretching force}}}$.	$\dfrac{4n}{\sqrt{2{\cdot}8}} = 2{\cdot}39n$	$\dfrac{5n}{\sqrt{4{\cdot}4}} = 2{\cdot}39n$	$\dfrac{6n}{\sqrt{6{\cdot}3}} = 2{\cdot}39n$	$\dfrac{8n}{\sqrt{11{\cdot}}}$ $= 2{\cdot}3$

Thus frequency $\div \sqrt{\text{stretching force}}$ gives a cons quantity ($2{\cdot}39n$ in our experiment) and so frequency is *portional* to $\sqrt{\text{stretching force}}$. The law may be forn stated thus: *For a string of constant length, the frequen vibration is proportional to the square root of the stretching f*

As in the case of the previous law (connecting frequ with length), we may use tuning-forks instead of a stret string. If we used the same forks as before, the 'frequ line of our results would read 256, 320, 384, 512, and in last line we should have

$$\frac{256}{\sqrt{2{\cdot}8}} = 153. \quad \frac{320}{\sqrt{4{\cdot}4}} = 153. \quad \frac{384}{\sqrt{6{\cdot}3}} = 153. \quad \frac{512}{\sqrt{11{\cdot}2}} =$$

Frequency and Mass per Unit Length. By experin somewhat similar to those already described it can be sl that the frequency of vibration of a wire is *inversely* portional to (i) its diameter, (ii) the square root of the de

he material of which it is made. It can be shown (by very difficult mathematics) that both these results are ıded in the statement *the frequency of vibration of a string ıversely proportional to the square root of the mass per unit th.*

athematical expression. If frequency is denoted by n, th by l, stretching force by t and mass per unit length by he laws stated on pp. 353–5 may be expressed thus:—

$$\text{(i) } n \propto \frac{1}{l}, \quad \text{(ii) } n \propto \sqrt{t} \quad \text{and} \quad \text{(iii) } n \propto \frac{1}{\sqrt{m}}$$

hree of which are combined in the statement

$$n \propto \frac{1}{l}\sqrt{\frac{t}{m}}$$

$$n = \frac{1}{l}\sqrt{\frac{t}{m}} \times k$$

e k is some constant.

l is measured in centimetres, t in dynes (= wt. in grams 31) and m in grams per centimetre of length, it can be n that $k = \frac{1}{2}$ and so $n = \frac{1}{2l}\sqrt{\frac{t}{m}}$.

ample 1. A steel string vibrates between two bridges 100 *cm.* , *the stretching force applied to it being* 10 *kilograms. One length of the wire weighs* 0·24 *gm. Calculate the frequency uning-fork which is in unison with this string.*

have to find n, given that $l = 100$, t (10,000 gm.) =) × 981 dynes and $m = \frac{0{\cdot}24}{100} = 0{\cdot}0024$ gm. per cm.

m the formula we have

$$n = \frac{1}{200}\sqrt{\frac{10{,}000 \times 981}{0{\cdot}0024}}.$$

s is best worked out by logarithms, and we get $n = 320$.

3. This exercise suggests a means of determining the ency of a tuning-fork, organ-pipe, etc. We stretch a ıeter string by means of a weight, and then by moving ridges make it give the same note as the fork. We ıre l (distance between bridges) in cm., and observe t ching force in gm. × 981). We get m by weighing a ı length of the wire and dividing by the number of cm.; en calculated from the formula.

Example 2. *A stretched steel string emits a note of freque 256 when vibrating under a certain tension. When the tension increased by 5 kilograms the note emitted by the wire is of freque 384. What was the original tension of the wire.* Lond.*

Let $x =$ original tension in kilograms.

Since frequency $\propto$ square root of tension, then

$$\frac{\text{1st frequency}}{\text{2nd frequency}} = \frac{\sqrt{\text{1st stretching force}}}{\sqrt{\text{2nd stretching force}}}$$

$$\therefore \quad \frac{256}{384} = \sqrt{\frac{x}{x+5}} \quad \text{or} \quad \frac{2}{3} = \sqrt{\frac{x}{x+5}}$$

Squaring, $\quad \frac{4}{9} = \frac{x}{x+5}$

Multiplying across, $9x = 4x + 20$

$\therefore \quad x =$ **4 kilograms.**

Or we could have used the full formula.

In the first case, $256 = \frac{1}{2l}\sqrt{\frac{1000x \times 981}{m}}$

,, ,, 2nd ,, $384 = \frac{1}{2l}\sqrt{\frac{1000(x+5) \times 981}{m}}$

$\therefore \quad \frac{256}{384} = \sqrt{\frac{x}{x+5}}$, giving $x =$ **4 kilograms** as before.

Production of harmonics. Pluck a sonometer wire AB in middle and observe the pitch of the note. Now touc lightly with your finger at its middle point M, pluck it at a point one-fourth of its length from one end and immediately afterwards remove your finger. The original note, say *doh*, gives place to the octave *doh'*.

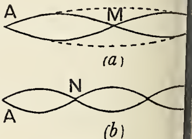


Fig. 30/6

At first the string was vibrating as a whole, or, as we sometimes say, 'in one loop' (dotted lines, Fig. 30/6*a*). The second time we kept the middle point M at rest touching it, and the string then vibrated in two loops lines, same figure). M, in fact, was made a node. AB vibrating as if it were two separate strings, AM and MB if we were gripping it at M with a pair of forceps.

And since each of the 'separate strings' was half the le of AB, it vibrated with double the frequency, and so gave the octave.

By touching the wire at N, one-third of its length from

l, and then plucking it (immediately afterwards removing finger from N), we make it vibrate in three loops, N being node (Fig. 30/6*b*). The note given out is now *soh'*, with ee times the frequency of the original note *doh*.

The lowest note given out by the wire vibrating as a whole alled the *fundamental* or *first harmonic* of the wire. The e given out when it is vibrating in two loops is called the ond harmonic, or first overtone. When vibrating in ee loops we get the third harmonic, or second overtone, so on.

n the experiments described above only one sound has n produced at a time, either the fundamental or one of the monics. In practice—e.g. when a violin is being played—fundamental and one or more of the harmonics are sound- *at the same time*, and the quality of the note depends on ch harmonics are sounding, and on their relative strength.

pplication to Instruments. It is interesting, and quite , to notice how the laws of strings—dependence of uency on length, tension, etc.—are illustrated by well- wn musical instruments. In the violin, for instance, the ring, used for the lowest notes, is the thickest, and the ring, for the highest, is the thinnest. Further, to increase mass per unit length, the G string is wound round with , silver-faced wire. The violinist tunes up by using the ng-pegs (one for each string) to increase or reduce the ion. Although he has only four strings, he can obtain note he wants by altering the effective length of the string, h he does by pressing it against the finger-board with his r.

the piano many of these features recur. The tuner sts the pitch by altering the tension of the strings with uning-hammer. For mechanical reasons, however, the er takes care that there shall be no great difference of on in different parts of the instrument, and he secures igh notes and low ones by making the strings for the er short and thin, while those for the latter are long and . The lowest are heavily wound with copper wire— two layers of it—to increase the mass per unit length. ecure extra length for the low-note strings, the piano is *over-strung*—i.e. the low-note strings pass diagonally

over some of those of higher pitch. Even in the ordina upright piano this diagonal arrangement often secures effective length of 4 ft. or so, while that for the strings highest pitch is scarcely as many inches.

Questions

1. Describe how you would verify the relation between length and frequency of vibration of a stretched string.

State the effect on the frequency if (*a*) the length and tens were both multiplied by four, (*b*) the thickness of the string w increased, the length and tension being kept constant. *J.M.B*

2. The lengths of the vibrating segments of a monoch (sonometer) when the wire was in tune with forks of the follow frequencies were as follows:

Frequency	100	150	200	250	300
Length (cm.). . . .	150·0	100·0	75·2	60·2	50

State the law to which you would expect these readings conform and verify that they do so, preferably by a suit graph.

What do you understand by the term wave-length? Calcu its value for a note given by a closed pipe, 16 ft. long, whic vibrating in its fundamental. *Camb.*

3. The tension in a wire 45 cm. long is 25 kg.wt., an vibrates with a frequency of 320 vibrations per sec. It is m to sound in unison with a musical note of frequency 360 vibrat per sec. by altering either (*a*) the tension, or (*b*) the length. F the required tension and length respectively. *Dur.**

4. Under a tension of 4 kilograms a certain wire 60 cm. gives a note of frequency 256, when vibrating. How could make it give a note of frequency 512, (i) altering only the len (ii) altering only the tension?

ANSWERS TO NUMERICAL EXERCISES

Answers to the odd-numbered questions only have been given

Chapter 13, p. 135

A	B
1. 212, 122, −40, 32, 59.	**1.** 3 cm.

Chapter 14, p. 143

.. 298° C. **3.** 182° C. **5.** 1·0051 c.c.; 8·889 gm. per c.c.
. 100 cm.

Chapter 15, p. 149

. 1·024 gm. **5.** 29·8 cm. **7.** 22 cm.

Chapter 16, p. 161

A

273, 288, 0, 373. **3.** (i) 546 c.c.; (ii) 746 c.c.

B

162° C. **3.** 233·2. **5.** 87·1 cm. **7.** 73·8° C.
1076 mm. **11.** 760 c.c. **13.** 91·0 or 91·1 c.c. **15.** 36° C.

Chapter 17, p. 172

A

380. **3.** (i) 0·855 cals.; (ii) 22·8 cals.

B

18·3 gm.; 0·45. **3.** 0·67. **5.** 707. **7.** 2·89 : 1.

Chapter 18, p. 182

A

(i) 100; (ii) 800; (iii) 1000; (iv) 5400. **3.** 76·4° C.

B

17·7° C. **3.** 132·5 gm. **5.** 3·03 cals. per gm. **7.** 0·132 gm.
1·25 gm.

Chapter 21, p. 219

A

3. 10.

B

1. 44·2. **3.** 1. **5.** 0·070° C.

Chapter 22, p. 247

B

7. 25 cm. in front; 1 cm.

Chapter 23, p. 260

1. 4 ft. **3.** (1) $1\frac{1}{4}$ ft.-candles (2) 2·83 ft. **5.** 0·6 ft.
7. 2·83 ft. from screen.

Chapter 24, p. 278

B

11. Reflected at $\angle 62°$ with normal.

Chapter 25, p. 290

1. $\frac{1}{3}$ cm. long; $13\frac{1}{3}$ cm. from lens, on opp. side.
3. $33\frac{1}{3}$ cm. from object; $44\frac{4}{9}$ cm. **5.** 8 cm.
7. $8\frac{4}{7}$ cm. from lens, same side as object (*a*) virtual; (*b*) erect

Chapter 26, p. 305

5. 3000 ft. **9.** -6 in.

Chapter 28, p. 335

7. 1650 ft.

Chapter 29, p. 347

5. 33,000 cm./sec.

Chapter 30. p. 358

1. (*a*) Halved. **3.** (*a*) 31·64 kg.wt.; (*b*) 40 cm.

PART III

MAGNETISM AND ELECTRICITY

CHAPTER 31

MAGNETISM. GENERAL PHENOMENA

Early history. There is evidence that man has been interested magnets for much more than 2000 years. These early agnets were found in the earth, and consisted of pieces of mineral now known to have been an oxide of iron with the rmula Fe_3O_4.

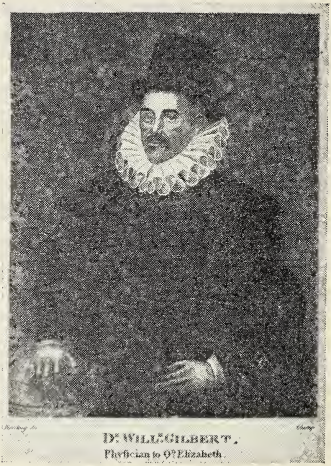
The first fact to be discovered was the obvious one that ey would attract pieces of iron. Much later, perhaps in e 12th century, it was found that a magnet if suitably spended, or if placed on a piece of wood floating on water, vays pointed in the same direction. But along with these portant facts, many absurd ideas were entertained. It s believed, for instance, that 'if a loadstone be anointed h garlic, or if a diamond be near, it does not attract iron'; l that 'if pickled in the salt of a sucking fish, there is power pick up gold which has fallen into the deepest wells.' h a stone might, of course, get into the wrong hands. It s 'of use to thieves . . . being a stone born as it were to theft'; it could even open bars and locks.

There were other dangers, too. There were actually untains in the north of such great powers of attraction t ships are built with wooden pegs, lest the iron nails uld be drawn from the timber.'[1]

Such was the state of knowledge mingled with fable when lliam Gilbert was born in 1544. He made many careful eriments which enabled him to distinguish the true from false, and writes very scathingly of the 'figments and ehoods, which in the earliest times, no less than now-a-s, used to be put forth by rare smatterers and copyists e swallowed of men.'

[1] The passages quoted are from the article on 'Magnetism' in the yc. *Britt.*, where they are mentioned as occurring in the translation lished by the Gilbert Club) of Gilbert's *De Magnete*.

Gilbert himself was a pattern of scientific honesty, settin down nothing as a fact unless he had verified it by experimen For instance, he carried out important experiments to show th the earth is a magnet. A full account of his work was given i his book, published in 1600, 'De magnete, magneticisque co poribus, et de magno magnete tellure'—*De magnete*, for short.



DR. WILLIAM GILBERT, PHYSICIAN TO QUEEN ELIZABETH

By courtesy of the Director of the Science Museum, South Kensington

He was a doctor, and in 1601 was appointed physici to Queen Elizabeth. In our earlier book there is a rep duction of a picture showing her and some of her ladies givi careful attention to a physics lesson.

The present chapter will consist of a review of the m elementary work, though in a few cases this will now be de with in greater detail.

Magnetic and non-magnetic substances. If a substance attracted by a magnet it is said to be *magnetic*; otherw

is *non-magnetic.* Iron (including steel) is the commonest gnetic substance. Nickel and cobalt, elements belonging the same chemical family as iron, are also magnetic, but ch less so than iron.

n 1903 F. Heusler prepared an alloy of copper, manganese l aluminium which was strongly magnetic. On the other id, during the war of 1914–18 Sir Robert Hadfield succeeded naking an alloy of steel and manganese which was non-gnetic.[1] Still, it remains broadly true that iron and steel strongly magnetic, and that other substances are not.

he medium. The medium through which magnetism ally acts is, of course, air. It is easy to show by experiment it acts readily through glass, wood, most metals—ough any common substance in fact *except iron.* Thus

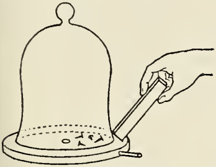


Fig. 31/1

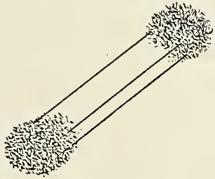


Fig. 31/2

n it is required to screen a substance from magnetic ence it is surrounded by an iron or steel casing.

agnetism also acts quite readily through a vacuum. This be shown by putting a few iron tacks under the receiver n air-pump, near the edge, and then pumping out the air. tacks are easily made to move about by a magnet held outside (Fig. 31/1).

agnetic poles. In a magnet as ordinarily magnetised, there wo points, near the ends, where most of the magnetic seems to be concentrated. This is easily seen by laying r magnet, or a horse-shoe magnet, on a sheet of paper which iron filings have been thickly sprinkled, and then ng it up. Thick clusters of filings are found to cling near nds, and very few anywhere else (Fig. 31/2). These points e the magnetic force seems to be concentrated are known

[1] he object was to make it impossible for the Germans, merely by a compass needle, to find when their vessels were nearing our mines.

as the ***poles*** of the magnet. The line joining the poles known as the ***magnetic axis.***

Direction. Fig. 31/3 shows a magnetised knitting-nee NS mounted so as to be able to swing freely in a horizon plane. (It is attached at A by a little plasticine to t rounded end of a test-tube, the latter being supported on t sharp point of a knitting-needle AB a little longer than itse It is found that the needle always sets in a particular direction, making (in England) a small angle with geographical north and south. We say that it sets 'in the magnetic meridian', a term which will be formally defined a little later (p. 376).

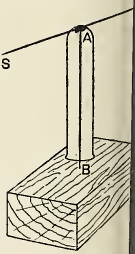


Fig. 31/3

Attraction and Repulsion. In Fig. 31/3 the pole N which points towards the north is known as the *north-seeking pole,* the other one being the south-seeking pole. 'Like' poles (e.g. two north-seeking poles) repel one another, while unlike poles attract.

For shortness, a north-seeking pole is usually called simply a *north* pole, but we must be car to avoid confusion. Since such a pole is always attrac towards the northern part of the earth, and it is un poles that attract one another, it follows that the north part of the earth behaves like the *south* pole of a mag When we speak of the earth's magnetic north pole, it is northerly *position* we have in mind. Compared with magnets in the laboratory, for instance, it is really a so pole.

Poles of equal strength. If we float a block of wood i trough of water, and across it lay a bar magnet NS, the bl turns round until NS is pointing in the usual direction. *does not move bodily however to one side of the trough,* and shows that the poles must be of equal strength. If, for instance, the south pole were stronger than the north, the block would soon drift towards the south side of the trough.

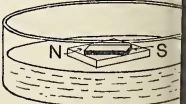
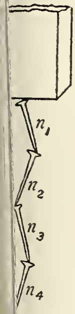


Fig. 31/4

It is interesting to notice that the earliest mariner's compass was very

ıch as represented in Fig. 31/4. An Arabic writer in a work date 1282, says that the needle was placed inside a reed, or a splinter of wood, and floated in a basin of water. In ıgh weather, however, it was probably useless.

Induction. If an iron nail n_1 is made to touch the end of a r magnet AB (Fig. 31/5), it sticks to it. There is nothing iking about that. If, however, a second nail n_2 is made to touch the lower end of n_1, n_2 sticks to n_1. Other nails n_3, n_4 may be added to the chain—half a dozen perhaps, the number depending chiefly on their weight and on the strength of AB.



. 31/5

If we grip the nail n_1 between thumb and finger and gently remove AB, the lower nails will at once drop off, though perhaps n_2 will continue to cling to n_1.

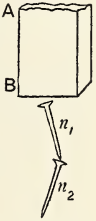


Fig. 31/6

Now, in the first instance, if the magnet AB had not been present, n_2 would not have shown the least tendency to cling to n_1. It is owing to the presence of AB that n_1 has been turned into a magnet. Then, in turn, n_2 has acquired its magnetic proper- from n_1, and so on through the chain. We say that n_1 been magnetised *by induction* from AB, n_2 by induction ı n_1, and so on. Magnetism by induction can take place ıout actual contact (Fig. 31/6), but in that case the effect ebler, and the chain of nails would be shorter.

the induced magnetism temporary or permanent? Our riment indicates that some of it is temporary, because lower nails dropped off on removing AB, but that some is more or less permanent, because n_2 remained sticking $_1$.

'e get further light on the question if we repeat the riment using (i) small pieces of *steel*—pen-nibs or bits lock-spring will do very well (Fig. 31/7*a*) and (ii) thin ıs of soft iron of about the same weight. These may be from a cocoa-tin (Fig. 31/7*b*). We find that we can e a much longer chain of soft iron than of steel. Thus soft iron n_2 in Fig. 31/7*b* must be a stronger magnet than

the steel n_2 in Fig. 31/7*a*, and so *soft iron is more strong magnetised by induction than is steel.*

But now let us gently remove AB. In the case of t steel nibs, n_2 will still cling to n_1. In the case of the stri of soft iron, there will be complete collapse. Thus *st retains its magnetism much better than soft iron.*

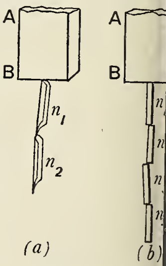


FIG. 31/7

The facts just mentioned are often expressed by saying that soft iron possesses greater *permeability* than steel, but less *retentivity*.

Testing for Polarity. If we bring the north pole of a bar magnet near the south pole of a magnetised needle (Fig. 31/8) it will certainly attract it; but if we bring it near the north pole it will *not* certainly repel it—it may attract it!

The reason is that the north pole of the bar magnet *induces* a south pole in the near end of t needle, and (if the bar is a much stronger magnet than t needle, as it probably is) this induced south pole more th neutralises the original north. Thus we now have unlike po near to one another, and attraction follows.

Attraction, then, is not a sure proof that two poles w originally unlike. To test our needle for polarity, we m bring up our testing magnet *slowly* to each end of the needle in turn. One end will then be repelled, and that, of course, is the end with polarity similar to that of the near end of the bar magnet. If in spite of bringing up our testing magnet slowly, both ends are attracted, it means t the needle, though made of a magnetic substance, has not b magnetised. Finally, if neither end of the needle is attrac we should conclude that it was made of some non-magn substance such as aluminium.

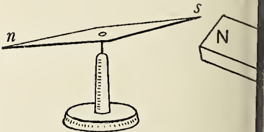


FIG. 31/8

How to make magnets. Two methods of making a mag are sufficiently indicated by Figs. 31/9*a* and 31/9*b*.

st is known as the 'single-touch' method, the second as ıt of 'double' or 'divided' touch. In both cases a south pole formed at B. We shall see later that a weak magnet may made by the help of the earth's field.

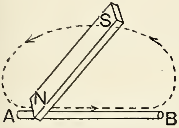


FIG. 31/9 (*a*)

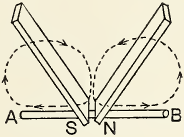


FIG. 31/9 (*b*)

'he modern method of making a magnet, however, is by ıns of the electric current (Fig. 31/10, where the coil is *nsulated* wire). If you put arrow-heads at the ends of the er N (Fig. 31/11), it will remind you that an *anticlockwise* rent is needed to give a north pole. Similar help is ained from the letter S (clockwise current).

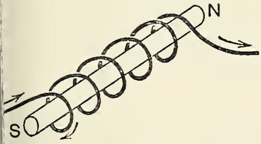


FIG. 31/10

FIG. 31/11

olecular theory of magnetisation. Straighten out a piece of x-spring about 4 inches long and magnetise it (Fig. 31/9a), cessary testing for polarity. With a pair of pliers break the ıg into halves, test each half ıagnetism. It be found that half is a ıet. The original poles are tered, but new have apped at the point of division. (Fig. 31/12b).

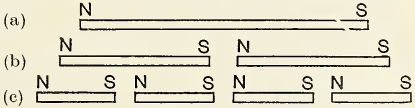


FIG. 31/12

eak each of the two magnets into halves. On examination found that there are now four magnets, with polarity as n in Fig. 31/12c.

In practice, of course, the bits of spring soon become t
short to be broken further, but it seems reasonable to suppo
that if we could overcome the mechanical difficulties we cou
just go on and on making new magnets until we reached ve
small particles indeed.[1]

We can now get a good idea of what happens when
magnetise a piece of steel. Fig. 31/13 represents the u
magnetised steel. Every particle is a magnet, a
for convenience the two poles have been distinguished by marking one end with an arrow. There is no orderly arrangement,

Fig. 31/13

but on the principle that 'unlike poles attract', most of t
particles would no doubt form themselves into closed cha
of three, four or more, the north pole of one particle touchi
the south pole of the next. Such a closed chain would sh
no free magnetism, because each 'north' would be neutralis
by the 'south' that touches it. Again, even if we consid
'free' particles, there would be just about as many pointi
in one direction as in another, and so the bar as a wh
would show no polarity.

Now suppose we stroke the bar with a magnet as shown
Fig. 31/9*a* (p. 367). The closed chains are broken up, and the particles set themselves somewhat as shown in Fig. 31/14, their south poles all pointing

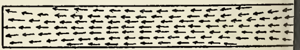


Fig. 31/14

towards the 'north,' which is passing over them. At one
the north poles are all pointing in the same direction, with
south poles to neutralise them, and so at that end the
shows north polarity. In a similar way it shows south p
rity at the other end. The central parts of the magnet sl
no polarity, because the north pole of one particle is tou
ing the south pole of the next.

[1] The very smallest particles would be molecules, but there is s
reason to believe that the limit would be not the molecule itself, b
cluster of molecules—what we have called a 'very small par
indeed.'

If we break our magnet into two, new poles are found at ch broken end because the particles were already pointing one direction—and so on, no matter how many times we eak it.

Confirmation of the theory. If it is true that a magnet owes properties to a special arrangement of its particles, we ght to find that if it is knocked about violently it should e its magnetism, because the knocking would upset the lerly arrangement.

That is just what we do find. The more a magnet is ocked about, dropped on the floor, etc., the weaker it omes.

Again, *heating* would produce violent agitation of the ticles, and so by shaking them out of their orderly arrange-nt should produce demagnetisation.

That also is found to be the case. In fact, if a magnet is de red hot and then cooled, it will be found to have lost magnetism completely.

Our theory suggests that there is a definite limit to the ree to which a piece of steel can be magnetised, the limit ng reached when the magnet particles have all attained end-on position. This also is borne out by experiment. nagnetising a piece of steel, a point is soon reached at which s 'saturated.'

Keepers. It is found that a horse-shoe magnet retains gnetism much longer if when it is put away, a short bar soft iron called a 'keeper' is placed across its ends (Fig. 15*a*). We can now see the reason. For clearness, the N has been drawn on a large scale (Fig. 31/15*b*). N uces' an opposite pole in the end A of the keeper, and the ll magnet-particles at the end of N are now held in position the magnet-particles at the end of the keeper; similarly, ourse, at the end S.

o apply the 'keeper' principle to bar magnets, they are away in pairs with their poles in opposite directions . 31/16) and keepers are placed across the ends.

emagnetising. We have seen that a magnet may be agnetised by heating it or by knocking it about violently, effect in either case being to disturb the orderly end-on ngement of the magnet-particles. A much better method,

however, is to use the apparatus already described for magneti
ing (Fig. 31/10), except that now we *must* use an alternati
current. The magnet is placed inside the coil (Fig. 31/17
the current is turned on, and then the magnet is slow

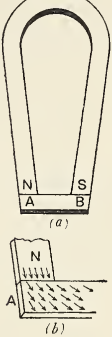


Fig. 31/15

Fig. 31/16

withdrawn. As the current surges first one way and th
the other, the polarity of the magnet is constantly reverse
at A, for instance, we have first a north pole and immediat
afterwards a south pole. But as the magnet is withdra
it is less and less exposed to the magnetising influence of t
current, and so it becomes weaker and weaker. When it h
been taken completely out of the coil and some distance beyond, the influence of the current becomes practically nil and the demagnetisation is complete. It is a good plan, however, to repeat the process with the magnet in the reversed position (i.e. A to the right).

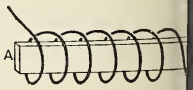


Fig. 31/17

Fields of Force. The influence of a magnet is, of cou
noticeable for some distance round it—iron filings are
tracted, or a compass needle is made to alter its directi
In the quaint language of Gilbert, 'From about a magneti

dy, the virtue magnetical is poured out on every side ɔund in an orbe.' The space throughout which the influence a magnet can be detected is known as its ***field of force.***

A complete knowledge of the field of force of a magnet ıuld mean that at any point in the field we know (i) the *ection* of the force and (ii) its *magnitude.* It is much easier obtain information about the first than about the second, l it is direction with which we shall be mostly concerned the present chapter.

Lay a strong bar magnet on the table, and over it lay a sheet drawing-paper. It is better to keep the paper level, and this

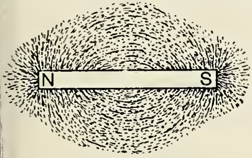


FIG. 31/18

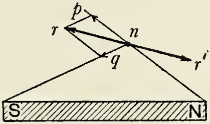


FIG. 31/19

be done by placing rulers, three-ply or something of the sort er its edges. Sprinkle iron filings over the paper as evenly ɔossible, using a pepper-pot. Now with the end of a pencil, the paper gently in different parts. The filings quickly set nselves in curves (Fig. 31/18).

et us try to make out what has happened. Each filing, ıuse it is in the neighbourhood of a magnet, becomes a ;net itself by induction. Suppose n is the north pole ɪne of these small magnetised filings (Fig. 31/19). It is lled from N by a force which we will represent by the np. It is attracted to S by a smaller force represented the shorter line nq (the force being smaller because the ınce is greater). We complete the parallelogram of :h np and nq are two adjacent sides and draw the diagonal nr represents the resultant force on the north pole of magnetised filing. The resultant force on its south pole be represented by nr', equal and opposite. If free to e, the filing will evidently set itself in the direction rnr'. 'as to give it freedom of movement that we tapped the :r. This caused the filing to give a little jump into the

air, and set it free for a moment from the frictional resista
of the paper.

For *every* filing, then, there is a definite direction in wh
it will arrange itself if free to do so; and when each filing
so arranged itself, the result is the curves we have obtai
in our experiment.

Going back to Fig. 31/19, we can see that if n were a
north pole, it would begin to *move* in the direction nr.
moment later, because it would be in a slightly differ
position, we should obtain a slightly different parallelogr
and its direction of motion would be altered a little. In f
it would move along the curve on which it lies. Such a cu
is known as a ***line of force,*** which we may formally defin
*the line along which a free north pole would travel as the re
of magnetic forces acting upon it.*

Actually we cannot obtain a free north pole—there
always a south at the other end of the magnet. Howe
we can so arrange matters that the influence of the south pole is scarcely felt.

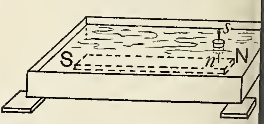


Fig. 31/20

A sewing-needle is strongly magnetised and passed vertically through a small cork, which is floated on water in a shallow trough. One end of the needle, say the north end, should nearly touch the bottom. The trough is suppo
just above a strong bar magnet, the north pole of which is
that of the needle. It will be found that the cork moves a
a curved path similar to those we have been considering.

You should now use the iron filings method to ob
records of the various cases represented by Figs. 31/2
31/26, afterwards comparing your results with the illustrati
(N.B. In these experiments, Robinson's *ball-ended mag*
are sometimes used instead of bar magnets. They have
advantage that as the magnetic pole is at the centre of
sphere, there is no vagueness about its position.)

Neutral points. Notice the point marked X in Fig. 3
If we imagine a free north pole in that position, it would
move, because it is equally repelled both from right and
It is known as a ***neutral point,*** which we may define
point subject to magnetic forces of which the resultant is

Other neutral points are indicated in Figs. 31/25 and 31/26. The presence of a piece of soft iron in a magnetic field roduces very marked changes. Figs. 31/27 and 31/28

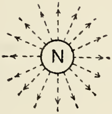


Fig. 31/21

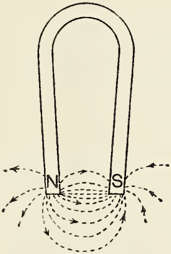


Fig. 31/22

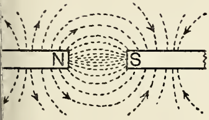


Fig. 31/23

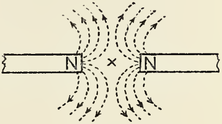


Fig. 31/24

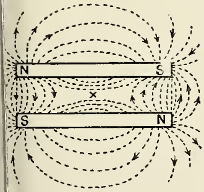


Fig. 31/25

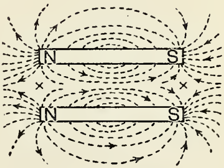


Fig. 31/26

uld be compared with Fig. 31/23. The lines of force are ier actually drawn into the iron, or are at least bent towards Inside the ring (Fig. 31/28) we have no lines of force.

Another way of considering these cases is to remember

that the soft iron becomes a magnet by induction (the pol
are marked with small letters). Each case then reduces
that illustrated in Fig. 31/23, except that the proximity

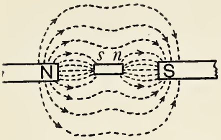


FIG. 31/27

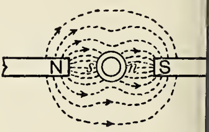


FIG. 31/28

unlike poles occurs twice over in Fig. 31/27 and also in F
31/28.

In Fig. 31/28 we should say that the ring serves as a *magn*
screen. V'e have a very good example of magnetic screeni

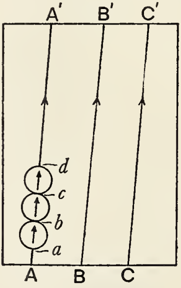


FIG. 31/29

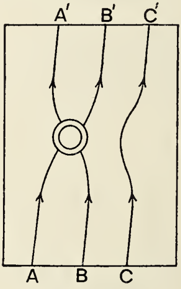


FIG. 31/30

in the case of a submarine. The lines of force due to
earth cannot penetrate the steel shell of the vessel, and so
needle of an ordinary compass would not point in any partic
direction. A gyro-compass, which works on an enti
different principle, is used instead.

Earth's field. The earth's field is too weak to cause i
filings to arrange themselves along lines of force. Howe
a small compass needle will give us the direction of the
of force at any particular point such as A (Fig. 31/29),

moving the compass steadily forward from *ab* to *bc*, *bc* *cd* and so on, we can obtain a line of force of any desired gth. We can then obtain other lines, BB′, CC′ . . . by rting from B, C. . . .

It is interesting to repeat the experiment, but this time ting a solid or hollow iron cylinder on its base in the middle the paper. We notice how the lines tend to be drawn into cylinder (Fig. 31/30).

Magnets in Earth's Field. Starting with a fresh piece of paper, a strong bar magnet in the middle of it, with its south pole nting (magnetic) north. Use your compass dle to obtain a diagram of the field, and npare your results with Fig. 31/31.

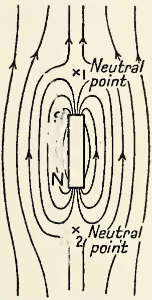


FIG. 31/31

Notice the neutral points X_1 and X_2. agine a free north-seeking pole at X_1. balance, it is attracted by the bar mag-, because the repelling force of N, which listant, is not so strong as the attrac- force of S, which is near. But its action to the bar magnet is balanced the attraction it experiences in the op-te direction, from the earth. Hence resultant of the magnetic forces is zero is a neutral point. The case of X_2 imilar. A free north pole placed there ld be, on balance, repelled by the magnet but equally acted by the earth.

$_1$ and X_2 are equidistant from the earth's north magnetic (a difference of two feet or so, in a matter of some hundreds housands of miles, 'doesn't count'). Hence a free north at X_1 would experience the same attractive force from earth as at X_2. Therefore, to balance, it must experience qual force in the opposite direction from the magnet—and X_1 and X_2 must be equidistant from the respective ends e magnet.

eclination. Most people know how to find the Pole Star. n looking at it you are looking almost exactly north. however, you possess a pocket compass, you will find the needle does *not* point to the north, but 10° or so to left (west) of it. We say that 'the *declination* is 10°

West.' This term is related to two others (*geographi meridian* and *magnetic meridian*) and it will be conveni to define all three of them now.

The ***geographical meridian at any point*** *is the plane wh passes through that point and the earth's geographical north a south poles.*

The ***magnetic meridian at any point*** *is the vertical pl passing through the axis of a compass needle placed at that poi*

The angle between the geographical meridian and the magn meridian is known as the ***declination*** *(or* ***variation****).*

These points are illustrated in Fig. 31/32. For sim practical purposes we may think of the declination as being the angle which our compass needle makes with a line running in a geographical north and south direction.

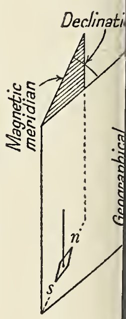


FIG. 31/32

Sailors and airmen, and often travellers on land, make use of a knowledge of declination (or variation, as it is still sometimes called). The compass gives them *magnetic* north, and from this, knowing the declination, they obtain *geographical* north—the north of the map. At one time it was thought that declination was the same at all points on the earth's surface. Columbus in 1492 was possibly the first to discover that this was not the case, and no doubt this added to the troubles of a very worrying voyage. was certainly the first to find a place where the declina was zero (not far from the island of Corvo, one of the Azo

Maps can be obtained in which lines are drawn throug points which have the same declination. These are kn as *isogonic lines*. The special isogonic line joining up places where the declination is zero is known as an *ag line* (actually there are two of these lines).

Declination not only varies from one place to another, at any one place it changes with time. In London, instance, it was 11° 15′ E. in 1580, zero in 1657 and 24 W. in 1818, since when it has been steadily decreasing. fact, a captain using an old set of tables might easily ru ship on the rocks.

Inclination or Dip. The earth behaves in many ways *as if* ıere were an immense bar magnet inside it, passing through ıe centre and making an angle with the line joining the ›ographical north and south poles (NP and SP in Fig. 31/33). ıis is, of course, not the case—for ıe thing, the earth's interior is far o hot—but the idea is often helpful. Such a magnet would have lines force somewhat as shown in the ure. At some places, such as A, ey would be parallel to the earth's rface, while at others, B and B′, ey would be at right angles to it. other points they would be in- ned at all sorts of angles between

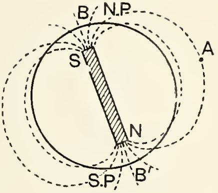


Fig. 31/33

e extremes of 0° and 90°. In London, for instance, the es of force actually make an angle of about 68° with the rizontal. If we can imagine a compass needle with a sort universal joint for its pivot, it would (in London) not only int magnetic north, but it would point downwards at an gle of 68°. Our imaginary 'universal joint' needle would ll be swinging *in the plane of magnetic meridian*, but it uld be inclined to the hori- ıtal *at the same angle as the th's lines of force.*

Now if a needle is to be free to line itself to the horizontal, it ›uld swing in a vertical plane, l this is the essential feature the *dip needle* as it is called e Fig. 31/34).

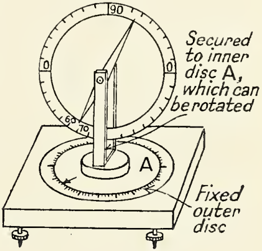


Fig. 31/34

The ***inclination*** or ***angle of*** › is *the angle made with the izontal by a magnetised needle, pivoted at its centre of gravity l swinging freely in the magnetic meridian.*

To find this angle we have to set the instrument so that graduated circle, over which the needle moves, lies in plane of the magnetic meridian. We might obtain this sition by using an ordinary compass needle, and then by

'sighting' arrange that our vertical circle in the edge-position just covers the line of the needle. This would invol using a second instrument, but actually we can obtain m accurate results without doing so.

In Fig. 31/35 suppose M and R are adjacent sides of ordinary box. Clearly the two planes are at right angl Suppose M is in the plane of the magnetic meridian, and th AT represents the earth's magnetic force in that plane, bo in magnitude and direction (we shall discuss the question magnitude in the next chapter). If from A we draw horizontal line AH and a vertical line AV, and complete the rectangle AHTV, we may regard AT as the resultant of a horizontal component AH and a vertical component AV.

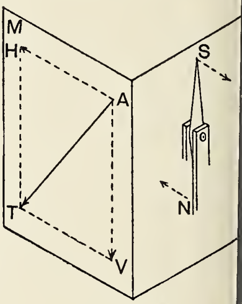


FIG. 31/35

Now suppose our dip circle is placed so as to lie in the plane R, at right angles to the plane M. N is the north-seeking pole of the needle, S the south-seeking pole. What will happen?

The horizontal component of the earth's magnetic force will attract N, and repel S, in the directions indicated by the dotted lines. But the needl so mounted that N and S can make no movement in th directions. Thus the horizontal component produces no eff except to cause a slight strain on the bearings.

The only effective force is the vertical component, wh will pull N vertically downwards. Evidently *when the pl of the dip circle is at right angles to the magnetic meridian, needle will set vertically.* In any other position the horizor component would have *some* effect, and the needle would set vertically. It is assumed, of course, that the needl pivoted at its centre of gravity; otherwise it would tend set vertically, quite apart from magnetic forces.

In using the instrument, then, we first see that the b is level (a good instrument includes a spirit level). We t rotate the base of the vertical pillar until the scale reading t

s that the needle is vertical. As just explained, the plane f the dip circle is now *at right angles* to the magnetic meridian, nd so by turning the base another 90°, we get it into the equired plane. We then take our reading, both ends of he needle, to eliminate any error caused by the needle not eing pivoted exactly at the centre of the scale.

We then turn the vertical pillar through an angle of 180° nd repeat the two readings. This is to eliminate any error aused by the zero line of the scale not being horizontal. We ow take the mean of our four readings.

To illustrate dip, we may suspend an unmagnetised knitting-eedle with fine cotton, so that it hangs horizontally. Its entre of gravity will, of course, be in the line of the cotton. Vith two bar magnets, using the method of double touch Fig. 31/9*b* on p. 367), we then magnetise the needle, taking re not to let the cotton slip along the needle. The latter ill now be found to tilt with its north pole downwards.

An early experiment. One of the first men to study the uestion of magnetic dip was a compass maker named Robert orman who lived in Wapping. He took great care to balance s compass needles as exactly as possible at their centre of avity, so that they should be level. When he afterwards agnetised them, however, the north end always tilted slightly wnwards. He soon suspected the cause, and actually nstructed a dipping-needle with which he found the angle dip to be 71° 50′. This was in 1576.

Five years later he wrote a book called 'The Newe Attrac-e.' He argued that somewhere under the earth there ust be a 'poynt Respective' towards which the needle turned, d by finding the direction of the needle at various parts of e earth's surface, and noting where the lines intersected, should be able to find it.

Norman, of course, was not in a position to do this, because e necessary information about the angle of dip was not ailable. It is quite easy, however, to do it now. The angles dip for some different latitudes on the meridian of Greenwich given at the top of p. 380.

Fig. 31/36 will suggest how to go to work. N and S resent the (geographical) north and south poles, and CQ part of the equator (lat. 0°). The latitudes are measured

	North								South				
Latitude (°) .	65	60	50	40	30	20	10	4	0	20	40	60	7
Inclination (°) .	75	72	68	59	48	31	10	0	10	38	54	62	9

as *angles* from CQ (only a few shown). Now to represent, f instance, the information 'Lat. 60°, Inclination 72°.' Join to the '60' point, K. This line is the vertical through K, i it points to the earth's centre. Draw the tangent KH. T is the horizontal at K. and the dipping needle would po as shown.

Do your arrows give any rough idea of the position of t earth's magnetic poles?

Isoclinic Lines. We have seen that the inclination London is 68°. There are many other points on the earth's surface which have the same inclination—in Germany, Russia, Siberia, the United States and elsewhere. If we draw a line joining up all points having the same inclination we obtain what is called an ***isoclinic line,*** or ***isoclinal.***

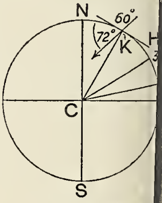


Fig. 31/36

An ***aclinic line*** is a line joining points where the angle of dip is zero.

On the theory that the magnetic properties of the earth are such as would be produced by a magnet placed somewhat as in Fig. 31/33 we should exp to find magnetic north and south poles—points where the would be 90°—in the far north and far south respectively, w an aclinic line following roughly the direction of the ear equator. Isoclinic lines we should expect to follow, rougl lines of latitude.

Actually a south magnetic pole has been located in 71° 10′ S., long. 150° 45′ E. (Mawson, 1914) and a no magnetic pole in lat. 73° 15′ N., long. 94° 30′ W.[1] Compari

[1] The latter position is given by the Canadian Dominion Observat It is deduced from observations made during the flight of the A (R.A.F., under Wing Commander McKinley, May 1945), together land observations made later. For this information the autho indebted to the courtesy of the secretary of the Royal Geograpl Society.

ith earlier observations suggests that these positions alter ıther rapidly. Thus Roald Amundsen in 1903–06 gave the osition of the north magnetic pole as 71° N., 96° W., while 1831 it was 70° 05′ N., 96° 46′ W. (James Clark Ross).

The aclinic line does indeed follow roughly the direction the equator, never being more than about 10 degrees north south of it. The isoclinic lines cannot be said to follow ry closely the lines of latitude, especially in the southern misphere. However, their general direction is east and est.

No doubt the 'single bar magnet' theory is too crude to ıd to very accurate results. By supposing a second magnet be present, we find that theoretical and actual values for e angle of dip at different parts of the earth's surface ree much better, and the agreement can be still further proved by increasing the number of imaginary magnets. ıt the theory then becomes too complicated to be very eful.

Near the Magnetic Pole. The behaviour of a mariner's mpass in the neighbourhood of the earth's north or south ıgnetic pole might be expected to be troublesome. One l would have a strong tendency to turn downwards. rther, the tendency of a compass to point north and south pends on the *horizontal* component of the earth's magnetic ce (cf. Fig. 31/35 on p. 378), and near the poles this nponent is nearly zero.

Keeping these points in mind, it is interesting to note the lowing passage from a letter written in 1911 by Lieut. R. Bowers.[1] 'The compass required standing still to look it every time. Our sledging compasses are spirit ones, l as steady as a small hand compass could possibly be. u will understand, however, that owing to the proximity he magnetic Pole the pull on the needle is chiefly downwards. is forced into a horizontal position by a balancing weight the N. side, so it is obvious that its direction power is atly reduced. On the ship, owing to vibration of the ines and the motors, we were absolutely unable to steer

[1] In company with Capt. Scott, Wilson, Oates and Evans he reached South Pole on 18th January, 1912, but the whole party perished he return journey.

by the compass at all when off the region of the Magne
Pole'.[1]

We have a similar effect, of course, in the neighbourh
of the north magnetic pole. Cf. the following little pass
from 'Plowing the Arctic' by G. J. Tranter '. . . the weat
had suddenly become dirty with a strong wind, and it w
unsafe to proceed, for now the compass was entirely unrelia
owing to the proximity of the Magnetic Pole, and they h
to be able to see their way, needing the land for a guide.'

Magnetising Effect of Earth's Field. We know that a pi
of iron or steel, in the neighbourhood of a magnet, become
magnet itself by induction (p. 365). We should theref
expect that an iron rod which has been lying in, or nearly
the magnetic meridian would be magnetised, and especi
if it has been sloping at an angle of about 68°.

Actually we are much more likely to meet with iron r
(railings, for instance) 'sloping' at 90° than at 68°. It
interesting, using a pocket compass, to test these for pola
(the compass must, of course, be brought up *slowly*). T
lower end will usually be found to repel the north-seeking e
showing that it is north-seeking itself. Garden spa
forks, etc., may also be examined. The writer found t
his garden spade, and every prong of his garden fork, sho
north polarity at the bottom, as did two lengths of 'a
iron,' which had been placed in an upright position for fenc

Questions

1. Make a list of the chief properties possessed by a mag
and describe how you would demonstrate each of these proper
How would you show that the poles of a magnet are of e
strength but of opposite polarity? *C.W.B.*

2. A magnet usually attracts a piece of soft iron; repulsi
a property observed with permanent magnets. Explain. *O.*

3. How would you magnetise a bar of soft iron by (*a*) suit
stroking the bar, (*b*) a method of magnetic induction, (*c*) u
an electric current? Illustrate by diagrams which indicate
polarity acquired.
What do you consider takes place inside the iron bar du
magnetisation, and how do you explain the fact that there
limit to the intensity of magnetisation of the bar? *Dur.*

[1] Quoted from *The Worst Journey in the World*, by A. Ch
Garrard.

. Explain the following:—

a) If the N. pole of a strong magnet is held at some distance from the N. pole of a weak magnet, it repels it, but if it is brought close to it, it attracts it.

b) It is possible to magnetise a steel knitting needle so that there are north poles at both ends, and a steel ring so that it has no poles at all.

) When a magnet is broken or cut into two pieces, each piece is a complete magnet. *Camb.**

How would you demagnetise a bar magnet?

Explain the terms *pole of a magnet*, *magnetic line of force*, *netic field*, *neutral point*.

escribe how you would plot the lines of force in the neighbour-d of a bar magnet, placed with its axis in the magnetic idian, and with its North pole pointing south.

raw a diagram showing the lines of force, marking their ctions and indicating the positions of the neutral points. *C.W.B.*

Explain the meaning of the terms *magnetic variation* (or *nation*) and *magnetic inclination* (or *dip*).

escribe how you would measure *one* of these quantities in the ratory.

ow how an approximate magnetic model of the earth can nade by suitably placing a magnet inside a sphere. Give a ram. *J.M.B.*

Explain why the needle of a dip-circle points vertically wards when the plane of the dip-circle is at right angles e magnetic meridian.

'The latter [i.e. a knitting-needle suspended at its c.g. and magnetised] will now be found to tilt with its north pole wards' (p. 379).

hat difference, if any, would you expect to observe if you ed out this experiment at some place in the southern sphere, e.g. Melbourne?

If you were provided with an unmagnetised steel knitting e, how would you use it to demonstrate magnetic dip? details of your method of magnetising the needle.

plain, giving reasons, how you would magnetise a piece of as strongly as possible in the earth's magnetic field. *C.W.B.**

CHAPTER 32

MAGNETIC MEASUREMENTS

In his age-long history man has always been engage exploring the world around him. He has been intere in finding where rivers have their source; he has wante know what lay on the other side of a range of mount or beyond the ocean. In his ceaseless enquiries he has ceeded so well that, in its main outlines, geograp exploration may be regarded as complete.

But geographical exploration is only one part of the q We see the point very well illustrated in Scott's exped to the Antarctic, already referred to in these pages. Cert his work had a geographical side, but he took with h remarkable team of highly trained scientists, who bro back with them a wealth of information about wind velo and air temperatures, atmospheric humidity, the depth salinity of the ocean and the plant and animal life cont in it. The magnetic laboratory was set up in a cave small glacier. There, by an ingenious arrangement included a clockwork mechanism, they obtained conti records of the direction and intensity of the earth's ma force. There, too, they made careful measurements o clination and inclination, and of other values which we be considering in the present chapter. The illust (from *The Great White South*, by H. G. Ponting) Dr. Simpson making observations with his magnetome

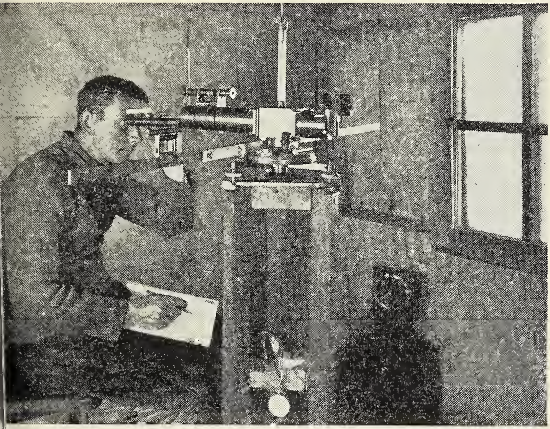
Let us get rid of the idea—if we have it—that the su of magnetic measurements is 'just school stuff.' It *is* s stuff, of course, but it is exploration stuff as well, an more we know of it, the deeper will be our interest in th story of world exploration.

Pole strength. As is always the case, we find that we c make measurements until we have fixed upon a suitable and we shall begin by considering a unit in which w express the strength of a magnetic pole.

We know that like poles repel one another with a c force. The stronger they are, and the nearer they are tog

e stronger the force of repulsion. Now, we already have a unit force, the *dyne* (p. 33), and this helps us to fix the new unit are considering. ***Unit magnetic pole*** *is one of such strength t it will repel a similar pole, placed one centimetre away from n air, with a force of one dyne.* This unit pole has been en the name ***Weber.***[1]

Ve shall have need almost at once of another definition



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DR. SIMPSON MAKING MAGNETOMETER OBSERVATIONS IN THE ANTARCTIC

ected with unit pole. The ***intensity of a magnetic field ny point*** *is measured by the force which would be experienced unit north pole placed at that point.* The name given to unit is the ***oersted***[1] or ***gauss***.[1] In London, for instance, it north pole would be attracted with a force of about dyne. We say, then, that the intensity of the earth's etic field, in London, is 0·18 oersted.

is implied in the definition of the weber—even if we had known it already—that the force of repulsion varies with

[1] Veber, Oersted and Gauss were eminent 19th-century physicists. ed was a Dane; the other two were Germans.

the distance. But to what extent? If the distanc doubled, is the force simply halved, or what? That is question we must try to answer. In doing so, we shall m use of an instrument called a *magnetometer*, or *defle magnetometer*, and we will consider this instrument first.

Deflection Magnetometer. Suppose a short magnetic ne *ncs* has a bar magnet placed on its east or west side. In Fig. 32/1 this is supposed to be well to the east (lying on an east–west line passing through the centre of the needle), but too far off to appear in the diagram. Its south pole faces the needle. Because of its distance, and the shortness of *ns*, we may suppose it to be opposite either *n* or *s*.

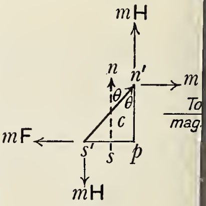


Fig. 32/1

Let H be the field due to the earth. Then *unit* pole would experience an attractive force H, so if m is the str of the pole at n', the attractive force is mH. At s' we ha equal and opposite force. These two forces make up a c (p. 82), with a moment or turning power of $m\text{H} \times ps'$.

Similarly the magnet (on the east) gives rise to a cou moment $m\text{F} \times pn'$, where F is the field at (and very ne due to the magnet.

As the needle is stationary, the two moments must bal so $m\text{H} \times ps' = m\text{F} \times pn'$, or $\text{F} = \text{H} \times ps'/pn' = \text{H}$ ta

We will now notice how the magnetometer is constru and we shall then see that this relation F = H tan enable us to answer our original question—viz., how i *force* between two magnetic poles related to the *di* between them?

The central feature of the magnetometer is a *small* ma needle *ab* pivoted on a vertical support (Fig. 32/2). It be small so that the field in which it moves may be reg as uniform; otherwise we should have hopeless complica But it is much easier to take angular readings with a needle than a short one, and so a long aluminium poin crosses the magnetic needle at right angles. Its ends

er a scale showing degrees. Inside this is a circular sheet mirror glass, and when taking a reading we take care that e pointer just 'covers' its image. In this way we avoid e error of parallax. The needle and scale are enclosed in a uare frame, opposite sides of which contain slots S_1 and S_2. to these slots are fitted two rather long wooden arms so aduated as to show the distance in centimetres from the itre of the instrument. From the end-on view it will be n how the arm is so shaped that a magnet can conveniently placed on it, touching the graduation marks. The arrange- nt is such that the magnet is exactly opposite the centre the needle.

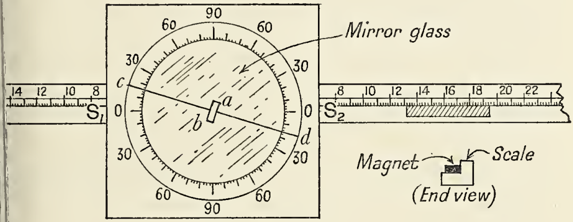


Fig. 32/2

'aking care that no magnets or iron work are near, we vly turn the magnetometer until the aluminium pointer ver the zero of the scale. (There is sometimes a slight erence between the readings of the two ends, due, e.g., he pointer being bent. In that case the mean of the two dings must be zero.)

'ow comes our first real difficulty. We are investigating field produced at the centre of the instrument by *a* pole ur magnet. But the magnet has *two* poles, and the second will simply upset our results. If we use a really long net, however, this second pole will be so far away as not ause very serious disturbance; so we use a magnet of ting-needle shape, at least 45 cm. long. Its poles are tically at the ends. We start with one end about 15 cm. 1 the needle and observe the deflection (reading both ends he needle and taking the mean). We then repeat at

distances increasing by 2 or 3 cm. each time. Suppose
obtain the following results:—

Distance in cm. (d)	θ	H tan θ	H tan $\theta \times d$	H tan $\theta \times$
15	36·8	0·7481 H	11·2 H	168 H
18	27·1	0·5117 H	9·22 H	166 H
20	22·5	0·4142 H	8·28 H	166 H
22	19·2	0·3482 H	7·66 H	169 H
25	15	0·1679 H	6·70 H	167 H

H tan θ is the field at the centre of the circle, due to magnet (F = H tan θ); it is the force that would act o unit pole placed there. When we multiply this force by distance (H tan θ × d), we obtain very variable produ (11·2 H, 8·28 H, etc.); but when we multiply it by dista *squared* (H tan θ × d^2), we notice that the answers are practica constant, showing that the force varies inversely as the *squ* of the distance. This result, known as the ***Law of Inve Squares***, is so important that we had better have a for statement of it.—*The force of attraction or repulsion betw two magnetic poles varies inversely as the square of the dista between them.*

In the experiment just described we get rid of the act of the unwanted pole by using a very long magnet. Anot method sometimes used is to arrange a magnet with unwanted pole vertically above the centre of the magn meter needle. In that position it is unable to deflect needle, and so all deflection effects are due to the other p Diagrammatically, two positions of the magnet are show Fig. 32/3.

The following experiment gives an indirect but very g proof of the law of inverse squares. We begin by *assum* the truth of the law. We then work out certain results should follow if the law is true. We prove by experiment these results *do* follow, and we conclude that our orig assumption must have been correct. Let us now cons the experimental work in detail.

Draw the outline of a bar magnet on a large sheet of pa and mark the positions of the poles, N and S. We shall

far out if we put them at one-twelfth the length of the gnet from each end (Fig. 32/4).

Iark any point P on the paper, and *assuming the truth he law of inverse squares*, find which way a free north pole ıld move if placed at P. To do so join NP and SP and duce NP to Q. Measure NP and SP and square the results. pose NP = 15·2 cm. and SP = 9·8 cm. We have $2^2 = 231$ and $9{\cdot}8^2 = 96$.

ow, a free north pole would be repelled along PQ, but acted along PS. If the forces of attraction and repulsion e *directly* proportional to the squares of the distances, we ıld mark off a length of 231 units along PQ and 96 units g PS. But the forces are *inversely* proportional, so we

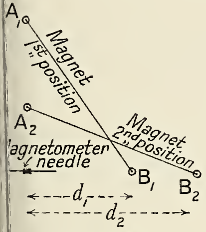


Fig. 32/3

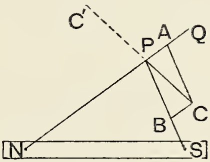


Fig. 32/4

k the 96 units along PQ and 231 units along PS. A enient unit would be, say, 1/40th cm. Then 96 units = m. and 231 units = 5·78 cm. In the figure, then, we k off PA = 2·4 cm. and PB = 5·78 cm.

PA and PB represent, in magnitude and direction, the s acting on our free north pole, its *actual* direction of ement would be along PC, the diagonal of the completed llelogram.

w, suppose a compass needle to be placed at P. Its pole will be driven along PC. Clearly the forces acting s south pole, though the same in magnitude, are opposite rection, so this south pole would be driven along PC′. needle should evidently set in the direction C′PC.

place the bar magnet and place a compass needle at P. will find that it actually sets along the line CPC′.

This *might* be the result of an odd coincidence, so re the work for several other positions of P. We find that two directions agree every time. Other members of the c all report the same agreement. We are therefore boun conclude that the assumption underlying all our calculat is true—and that assumption is the Law of Inverse Square

Mathematical Expression. In calculations connected magnetism, we shall find that we are again and again ma use of the following statement: *If a magnetic pole of streng units is* d *centimetres from another pole of strength* m′ *u the force of attraction or repulsion between the two pol* $\frac{mm'}{d^2}$ *dynes.* (It can easily be shown that this follows f the law of Inverse Squares.)

N.B. Unlike poles are expressed by opposite signs. a north pole of 6 units and a south pole of 8 units woul expressed as $+ 6$ and $- 8$. If they were 4 cm. apart, force between them would be $\frac{(+6) \times (-8)}{4^2} = -3$ d the minus answer indicating that the force is one of attrac

Some applications of the Law. We have just had one simple application—finding the force of attraction bet two poles at a given distance apart. Here is a slightly h one:—

Example 1. *A bar magnet 12 cm. long and of pole streng units is placed horizontally in an east–west position, with its pole pointing east. Calculate the field strength at a point P, 1 east of the south pole, on the prolongation of the axis.*

The *field strength* at P means the force which would be experienced by a unit north pole placed there (p. 385).

In calculations where there is no statement to the contrary it is to be assumed that the poles are at the ends of the magnet.

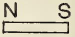


FIG. 32/5

Distance of P from S = 12 cm. (Fig. 32/5).

∴ unit north pole at P would experience a force of -3

$= -\frac{1}{4}$ dyne.

Distance of P from N = 12 + 12 = 24 cm.

∴ unit north pole at P would experience a for $\frac{36 \times 1}{24^2} = \frac{1}{16}$ dyne.

Both forces act along the line NSP, and the resultant is force of $-\frac{1}{4}+\frac{1}{16}=-\frac{3}{16}$ dyne, the sign indicating that he resultant force is one of attraction. Thus the *strength* of he field at P is $\frac{3}{16}$ **oersted.** Its *direction* is along PS.

Magnetic Moment. The field produced by a magnet depends artly, of course, on the strength of the magnetic poles. But also depends very much on the length of the magnet, specially at points in the direction of the axis.

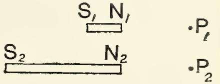


Fig. 32/6

For instance, suppose N_1S_1 is a hort magnet and N_2S_2 is a long one. heir poles are of equal strength. $_1$ is a point in S_1N_1 produced, and $_2$ another point in S_2N_2 produced. $_1N_1$ is equal to P_2N_2.

Now, if we had to consider only the poles at N_1 and N_2, e field at P_1 would be of the same strength as at P_2, because e distances are the same, and the poles are of the same rength.

But in both cases the strength of the field due to the north les is *weakened* by the fields due to the south poles at S_1 d S_2. This weakening effect is not so great in the case of e longer magnet, because S_2 is farther away from P_2 than is from P_1. Thus the resultant field due to the long magnet stronger than that due to the short one.

Because the field produced by a magnet may be affected its *length* as well as by its *pole strength*, we often have use a quantity which includes both of these. This quantity known as the ***moment*** of the magnet, and is obtained by ltiplying the pole strength by the magnetic length of the gnet (magnetic length = distance between poles). It can sily be shown that the magnetic moment as just defined is ual to the moment of the couple (p. 82) required to keep the gnet at right angles to a field of unit strength.

Comparing magnetic moments. We have seen that if a rt magnetic needle is deflected from the meridian through angle θ by the action of a magnet placed on its east or st side, then $F = H \tan\theta$, where F is the field produced the deflecting magnet at the centre of the short needle 386, Fig. 32/1).

Now, if M is the moment of the magnet, and if its length short compared with d, the distance of its centre from th needle, it can be proved that $F = \frac{2M}{d^3}$. But $F = H \tan$

Hence under these conditions $F = \frac{2M}{d^3} = H \tan \theta$.

To compare the moments of our two magnets we procee as follows:—

We set our magnetometer with the pointer at the ze of the scale—i.e. arms pointing east and west, as in Fig. 32 on p. 387. We then place our first magnet so that its midd point is 30 or 40 cm. from the centre, say on the east side the needle, and observe the deflection θ_1.[1]

We repeat with the second magnet, its middle point bei in the same position as before. Call the deflection th time θ_2.

If M_1 is the moment of the first magnet and M_2 of t second, then in the first case $\frac{2M_1}{d^3} = H \tan \theta_1$, and in t second $\frac{2M_2}{d^3} = H \tan \theta_2$.

$$\therefore \quad \frac{M_1}{M_2} = \frac{\tan \theta_1}{\tan \theta_2}.$$

e.g. if $\theta_1 = 32{\cdot}3^\circ$ and $\theta_2 = 44{\cdot}7^\circ$

we should have $\frac{M_1}{M_2} = \frac{\tan 32{\cdot}3^\circ}{\tan 44{\cdot}7^\circ} = \frac{0{\cdot}6322}{0{\cdot}9896} = \frac{1}{1{\cdot}57}$.

In the experiment just described we have only *compa* the moments of two magnets. If the value of H is kno we can find the actual value, for $\frac{2M}{d^3} = H \tan \theta$, and if know the values of H, d and θ we can obviously calcul M. Lastly, M = (*magnetic length*) × (*pole strength*), so we find the strength of the poles by dividing M by the magn length.

Comparing values of H. With a short bar magnet an magnetometer we could easily compare the values of H

[1] Reading both ends of the needle and taking the mean. In accurate work, we should now repeat with the magnet reversed for end, and then take the same four readings again but on the side of the magnet. θ is taken as the mean of all eight readings.

wo different places. All we have to do is to put the bar ıagnet at the same distance from the needle on both occasions, nd read the deflections, say θ_1 in the first case and θ_2 in ıe second.

Now the field produced at the centre of the compass needle given by $F = H \tan \theta_1$ and since the same bar magnet was sed in each case, at the same distance, it must have produced ıe same field. If on the first occasion H had the particular ılue H_1, and on the second occasion the value H_2, then $= H_1 \tan \theta_1$ and $F = H_2 \tan \theta_2$.

$$\therefore \quad H_1 \tan \theta_1 = H_2 \tan \theta_2.$$

$$\therefore \quad \frac{H_1}{H_2} = \frac{\tan \theta_2}{\tan \theta_1}.$$

we know the actual value of H_1, we can obviously calculate at of H_2.

Magnetic Moment by the Neutral Point Method. When ıdying fields of force in our preceding chapter we came across rious examples of *neutral points* or *null ints*. Let us look again at the particular se of the neutral points observed when a r magnet is placed with its south pole inting north. Call them X_1 and X_2 g. 32/7).

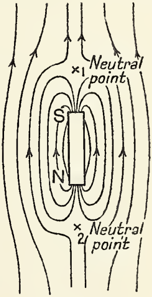


FIG. 32/7

A free north pole at X_1 would be lled northwards by the earth's 'north' ıgnetic pole (which is really south-king). From the magnet it experiences pull southwards from S and a push rthwards from N (like poles repel). N, wever, is more distant, so the magnet balance exerts a pull. It is because s pull southwards is equal to the earth's l northwards that X_1 is neutral or null—a point subject no resultant magnetic force. You can easily work out the e of X_2 for yourself.

Now suppose we could increase the strength of NS, while l keeping it in position. How would the position of X_1 be ected?

The earth's pull on our free north pole is what it was befor but the magnet's pull has increased, so X_1 is no longer neutral point—there would be a definite pull towards th magnet. If, however, the distance SX_1 is gradually increase the magnet's pull at X_1 becomes less and less, and a positi of neutrality is soon reached once more. In short, *for magnet of given length in the position we are discussing, th greater the pole strength, the more distant is the neutr point.*

Now let us go back—the magnet at its old strength and in its original position. Remove SN and replace it by a long magnet of the same pole strength, S being in the same positi as before (N, of course, will now be further 'down'). Agai how will the position of the neutral point X_1 be affected?

The earth's pull northwards is unchanged. S pulls sout wards with the same force as before, but N repels with *le* force because it is farther away. On balance, then, t magnet is pulling southwards with greater force than befo and so the neutral position is once more at a greater distan from S. Similarly for the other neutral point. *For a mag of given pole strength in the position we are discussing, greater the length, the more distant is the neutral point.*

Since the position of the neutral points depends on b the pole strength of the magnet and on its length, we are n surprised to find that it depends on the product of these— on the *moment* of the magnet. We can, in fact, find t moment of the magnet by determining the neutral point We shall first find the pole strength.

A long line is ruled in a north–south direction (Fig. 32/8), a good bar magnet is placed on it, south pole pointing nort

A sensitive compass needle is moved along the line u a position is reached in which it sets east and west. T distance of the centre of the needle from S, the south pole the magnet, is observed (S is approximately 1/12th of length of the bar magnet from one end). This gives position of X_1, and X_2 is obtained in a similar way.

[1] This can be done directly, i.e. without first finding the pole stren If $2l$ is the length of the magnet and $2d$ the distance between the neu points, it can easily be shown that $M = \dfrac{H(d^2 - l^2)}{2d}$.

Record the distances a, b, c and d shown in Fig. 32/8.

If we imagine a unit north pole at X_1, the force it ex-
periences from the magnet is $\frac{m}{a^2} - \frac{m}{b^2}$ where m is the pole
strength. This must be equal to H (say 0·18)

$$\therefore \qquad \frac{m}{a^2} - \frac{m}{b^2} = 0{\cdot}18$$

Knowing a and b, we can calculate m. Similarly at X_2, $\frac{m}{c^2} - \frac{m}{d^2} = 0{\cdot}18$, giving us another value of m. We take the mean of the two values.

Multiplying our mean value of m by the magnetic length of the magnet, we obtain the *moment*.

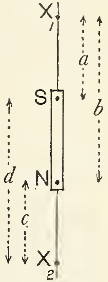


FIG. 32/8

Here is a typical result:—

Length of magnet was 10·2 cm., so the poles would be approximately 0·85 cm. from the end.

$a = 21{\cdot}9$ cm. $\qquad b = 30{\cdot}3$ cm.

$c = 22{\cdot}1$ cm. $\qquad d = 30{\cdot}5$ cm.

$$\frac{m}{21{\cdot}9^2} - \frac{m}{30{\cdot}3^2} = 0{\cdot}18$$

This gives $\qquad m = 181$ webers.

$$\frac{m}{22{\cdot}1^2} - \frac{m}{30{\cdot}5^2} = 0{\cdot}18$$

This gives $\qquad m = 185$ webers

Mean value $\qquad m =$ **183 webers.**

Magnetic length $\qquad = 10{\cdot}2 - 1{\cdot}7 = 8{\cdot}5$ cm.

∴ moment of magnet $= 183 \times 8{\cdot}5 =$ **1556 c.g.s. units.**

So far we have assumed that the value of H is known, and have been able to find the pole strength and moment of the magnet. Conversely, if the moment of the magnet is known, we can find H as in the following example:—

***Example* 2.** *The magnetic length of a bar magnet is* 10 *cm., an its moment is* 2000 *c.g.s. units. When the magnet is placed in th magnetic meridian with its south pole pointing north, a neutr point is found* 28 *cm. from the centre of the magnet. What val does this give for H?*

Referring to Fig. 32/8, a would be 23 cm. (28 cm. is the distan from the neutral point to the *centre* of the magnet), and b wou be 33 cm. Also m the pole strength

$$= \frac{moment}{magnetic\ length} = \frac{2000}{10} = 200 \text{ weber}$$

$$\therefore \quad \frac{200}{23^2} - \frac{200}{33^2} = H$$

giving H = **0·19.**

The Earth's Magnetic Field. A *quantitative* record of th earth's magnetic field at any place will, of course, first of a mention its direction. This is completely defined by statin the declination (i.e. so many degrees east of west of th geographical meridian) and the inclination (angle of dip In Fig. 32/9 we will suppose that AD represents the direction of the earth's magnetic force.

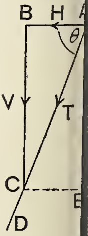


Fig. 32/

We have seen how to measure the horizontal component of this force, commonly called H. In Fig. 32/9 suppose this is represented in direction *and magnitude* by AB.

From B draw a vertical line BC meeting AD in C. Then BC represents the *vertical* component of the earth's magnetic field, while AC represents the total field. In Fig. 32/9 the parallelogram ABCE has been completed, and it should be clear that the total field AC is the resultant of a horizontal component AB and a vertical component (= BC).

If we know θ (the angle of dip) and H, we can easily calcul the vertical component V and the total field T, for $\frac{V}{H}$ = tan

so $V = H \tan \theta$. Also $\frac{H}{T} = \cos \theta$, so $T = \frac{H}{\cos \theta}$.

Alternatively, we can draw AD at the correct angle, draw horizontally of length to represent H, and complete the figu By measurement we can then obtain V and T.

Example 3. *If at a certain place the angle of dip is 68° and* $= 0{\cdot}180$ *oersted, find the value of the vertical component of the* *th's field, and also the total intensity.*

$$V = H \tan \theta = 0{\cdot}180 \times \tan 68^\circ$$
$$= 0{\cdot}180 \times 2{\cdot}475$$
$$= \mathbf{0{\cdot}446 \text{ oersted.}}$$

$$T = H/\cos \theta = 0{\cdot}180 \div \cos 68^\circ$$
$$= 0{\cdot}180 \div 0{\cdot}3746$$
$$= \mathbf{0{\cdot}481 \text{ oersted.}}$$

By drawing. Draw the triangle ABC of Fig. 32/9 making $= 68^\circ$ and $AB = 1{\cdot}8$ in., to represent 0·18 oersted. BC should found to measure 4·46 in. and AC 4·81 in. representing 0·446 sted and 0·481 oersted respectively.)

Questions

A

In the following cases m_1 and m_2 are the strengths of two netic poles, and d is the distance between them. Calculate force of repulsion between the poles.

i) $m_1 = 16$ c.g.s. units, $m_2 = 4$ c.g.s. units, $d = 8$ cm.
ii) $m_1 = 12$,, ,, $m_2 = 3$,, ,, $d = 6$ cm.
ii) $m_1 = 25$,, ,, $m_2 = 4$,, ,, $d = 5$ cm.

A north magnetic pole A of strength 25 c.g.s. units attracts uth pole B, 6 cm. away, with a force of 12 dynes. Find the gth of B.

Two magnets AB and CD are lying parallel to one another, their north poles adjacent and 2 cm. apart. The magnets l one another with a force of 27 dynes. What will be the of repulsion if their distance apart is increased to 6 cm.?

B

State the law of force between two magnetic poles. Two magnetised knitting needles are suspended parallel to each r and 2 cm. apart with their like poles adjacent. The needles repel each other with a force of 4 dynes. How far apart they be hung for the force to be reduced to 1 dyne? *Camb.*

2. Define *magnetic pole strength* and *magnetic field strengt*
A bar magnet 10 cm. long and of pole strength 40 units placed horizontally, in an east–west position, with its north po pointing east. Find, from first principles, the field strength a point P, 10 cm. east of the north pole on the prolongation the axis.
If the horizontal component of the earth's field is 0·2 oerste what is the resultant magnetic field at P? *Lond.*

3. State the law of force between magnetic poles.
The magnetic field due to a bar-magnet (length 20 cm., cro sectional area 0·5 sq. cm.) is 0·16 gauss at a point end-on to t magnet and 40 cm. from its centre. Calculate (*a*) the magne pole strength on the assumption that the poles are at the e of the magnet; (*b*) the average intensity of magnetisation.
State, with reasons, whether you consider this a suital method for measuring pole-strength. *O.C.*

4. Define the magnetic moment of a magnet.
Describe how you would compare the magnetic moments two short bar magnets.
Find the couple required to hold a bar magnet of pole streng 50 c.g.s. units and magnetic length 12·4 cm., so that it is at rig angles to a magnetic field of strength 0·2 c.g.s. units. *Oxf.*

5. Two bar magnets of magnetic moment 100 and 800 un respectively, are to be placed on the arms of a magnetometer, with its arms in an East–West direction, so that there is no c flexion. What must be the ratio of the distances of the magn from the needle? Explain your calculation. You may assu that the distances will be large compared with the lengths the magnets. *O.C.*

6. A short bar magnet A is placed 20 cm. from the needle o magnetometer used in the ordinary way, and causes a deflexi A second short magnet B is brought up on the opposite side the needle, A still remaining in place. When B is at a dista of 25 cm. from the needle the deflexion is reduced to zero. Co pare the magnetic moments of A and B. *J.M.B.**

7. Define *magnetic meridian* and *magnetic dip*.
With the use of a compass needle and a short bar mag describe a method for comparing the horizontal components the earth's magnetic field at two places.
Find the horizontal component of the earth's magnetic fi at a place where the total intensity of the field is 0·47 gauss a the angle of dip is 60°. *O.C.*

8. What is meant by a *line of magnetic force*?

A ball-ended magnet is placed in the Earth's field with its xis horizontal and in the magnetic meridian, and with its south ole towards the north. Draw a diagram of the lines of magnetic rce, marking the directions of the lines with arrows and indicat-g the positions of the neutral points.

If with a magnet in this position neutral points exist 15 cm. om the poles and the distance between the poles is 20 cm., lculate the pole strength and the magnetic moment of the agnet. (H = 0·18 gauss). *Camb.*

9. A bar-magnet of length 10 cm. and magnetic moment 1300 its is placed in the magnetic meridian with its north pole inting south. A neutral point is found at a distance 25 cm. om the centre of the magnet. Calculate the strength of the rth's magnetic field. *O.C.**

10. A bar magnet is placed with its axis in the magnetic eridian and north pole pointing south. Draw a diagram of the es of force which you would expect to find around the magnet. If the pole strengths of the magnet are 120 units, its length cm. and a neutral point is found 30 cm. from the centre of the gnet, calculate the strength of the horizontal component of e Earth's magnetic field. *O.C.**

11. A magnet is placed on a table with its north pole pointing th. If it is 10 cm. long and has a pole strength of 50 c.g.s. its, what is the magnetic field strength at a point 10 cm. from north pole and on the prolongation of the axis of the magnet? = 0·18 oersted.) *Lond.**

12. Two magnets, each of magnetic length 8 cm. and of pole-ength 40 and 60 c.g.s. units respectively, are placed so that y lie along the same straight line with like poles 4 cm. apart. culate the resultant force of repulsion between the magnets. *C.W.B.**

3. A bar magnet of magnetic length 12 cm. and moment 00 c.g.s. units is placed in the meridian with its south pole nting north. A neutral point is found 30 cm. from the centre the magnet. Calculate the strength of the earth's magnetic d. *O.C.**

4. In the magnetic observatory at Abinger (Surrey), for the r 1948, the following observations were recorded: Declination 35′ W. Dip 66° 46′. Horizontal component 0·1858 dynes unit pole.

xplain the meaning of each of these terms, illustrating your wer by diagrams. Calculate the vertical component and the l magnetic intensity.

CHAPTER 33

ELECTROSTATICS

A. Electrification by Friction

THE article on 'Electrostatics' in the *Encyclopaedia Britannic* occupies about seventeen columns. If there had been suc a publication in the days of the ancient Greeks it would hav occupied about seventeen lines, merely stating that whe *elektron* (amber) was rubbed with cloth it acquired the curio property of attracting very light particles, such as bits thread. The Greek schoolboy could acquire a complet knowledge of the science of electricity on very easy terms!

In electrostatics we are concerned with electricity at res as distinct from current electricity, a term which explai

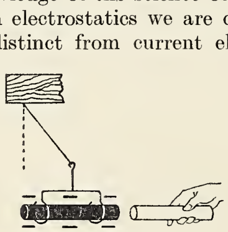


FIG. 33/1

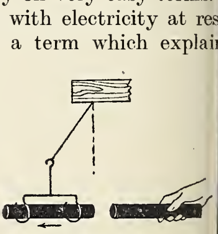


FIG. 33/2

itself. If we regard the one as resembling a lake, the oth is like a stream.

In these days we do not experiment with amber, but obtain similar effects by rubbing a vulcanite fountain p with cloth, or a glass rod with silk. The vulcanite or gla will then attract light bodies such as bits of paper, fragme of cork, etc. Thus *an electrified body will attract an u electrified one.* It follows from Newton's Third Law of Moti that an unelectrified body will attract an electrified one, b we can easily prove this directly. We support an electrifi vulcanite rod in a stirrup of copper wire suspended from silk thread (Fig. 33/1), and bring near it various unelectrifi bodies in turn—a book, a glass rod, one's hand, etc. In ea case the vulcanite is attracted.

Figs. 33/2, 3 and 4 show respectively

(i) an electrified vulcanite rod brought near another electrified vulcanite rod;

(ii) an electrified glass rod brought near another electrified glass rod;

iii) an electrified glass rod brought near an electrified vulcanite rod.

[n cases (i) and (ii) we have repulsion, but in (iii) we have raction. We conclude that *like charges repel one another, le unlike charges attract.*

Experiments such as the foregoing were made by Dr. lliam Gilbert of Colchester, late in the sixteenth century. found that he was unable to obtain any results with certain

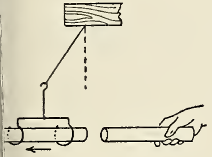


Fig. 33/3

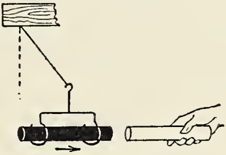


Fig. 33/4

s, particularly if they were made of metal. He wrongly cluded that such rods could not be electrified, and called n *non-electrics*, substances such as glass being *electrics*. now know that his 'non-electrics' were really *conductors* lectricity, so that the charges leaked away as fast as they e produced. If a brass rod is mounted on an insulating dle (e.g. one made of vulcanite), it can be electrified by ion in the usual way.

odern Theory of Electrification. Franklin, a famous -century experimenter, believed that whatever electricity ht be, there was only one kind of it, and all bodies essed it. When a body held its normal supply it was 'uncharged'—had no power of attracting bits if paper, In certain circumstances, however—when rubbed, for ance—it might gain electricity, in which case it was tively' charged. Or it might lose it, and then its charge 'negative.' This simple theory explained the known

facts very well. During the last fifty years, however, o knowledge of the nature of the atom has greatly increas and this has led to the following view of the nature electricity.

Probably you know from your studies in chemistry th though a small portion of an element—lead, for instance can be divided into halves, quarters, eighths, sixteenths a so on, this subdivision cannot go on for ever, even if we h a knife of infinite sharpness and sight of infinite keenn We come at last to the atom.[1]

The atom is inconceivably small, something like 10^{-8} c in diameter. This conveys very little meaning to us. I imagine an enormous goods-train stretching right round world at the equator—25,000 miles—every waggon in being loaded up with wheat. The number of grains of wh would be far less than the number of molecules of hydro in a cubic centimetre (the molecule of hydrogen consists two atoms); and remember that a cubic centimetre is m less than a thimbleful, and that the molecules are by means closely packed, either!

But small as is the atom, it has a *structure*, and inclu parts which are very much smaller than itself. These p are of three different kinds—electrons, protons and neutr *All* the different atoms—lead, hydrogen, sulphur, et contain these parts. Different numbers of them, and diffe arrangements, give the different atoms (just as diffe numbers and arrangements of bricks, tiles, beams, etc., g us different houses).

The protons and neutrons are bunched together to f what is called the *nucleus* of the atom—the comparati heavy, 'solid' centre. It would seem that the electrons rev round the nucleus somewhat as planets revolve round sun. In fact, the solar system is something like an ator an immense scale, the sun representing the nucleus (mad of protons and neutrons) and the planets—Mercury, Ve the Earth, Mars, etc.—representing the electrons. And as the mass of each planet is only a tiny fraction of the s

[1] Strictly speaking, to a small group of atoms known as the *mol* Sometimes there is only one atom in the molecule, in which cas atom and the molecule are, of course, the same thing.

ass, so the mass of the electron is only a tiny fraction of e mass of the nucleus. In fact, the mass of an electron is ly about the 1800th part of the mass of one of the neutrons protons which make up the nucleus.

It will help to clear up our ideas if we examine Fig. 33/5 for minute. It represents an atom of iron, with a heavy nucleus ade up of protons and neutrons, and a number of electrons volving in various orbits about the nucleus. For simplicity e diagram shows these or-s as a series of concentric cles in one plane. It is cer-n that they are nothing like simple as this, but that is a nt which need not concern here.

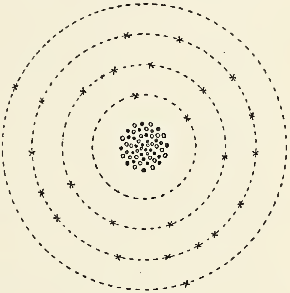


Fig. 33/5

t will be clear that an atom very *porous* structure. It ctually far more porous than diagram would suggest, on the scale to which the leus is drawn, the outer or-should have a diameter of or 30 ft.! Scientists have ually succeeded in bombarding the atom (using neutrons heir 'bullets') and they find that for every bullet that hits central nucleus, thousands go clean through.

t is certain that the electron is negatively charged. It ears, in fact, that the electron *is* a negative charge, and negative electricity is, so to speak, 'granular,' consisting lectrons, every one of which represents an equal charge.

ow, the atom as a whole, nucleus plus electrons, is elec-lly neutral. Since the electrons are negative charges, it ws that the nucleus must contain a balancing positive ge. The latter is contributed by the protons. The n of iron, for instance, contains 26 protons [1] (represented ig. 33/5 by small white circles), and the 26 positive charges

[1] And 30 neutrons. As regards mass, 1 neutron = 1 proton (approx.) this is practically the chemical unit of atomic weight. Thus, cting the very small weight of the electrons, atomic weight of = 26 + 30 = 56.

are balanced by the 26 negative charges represented by th electrons.

In certain circumstances the atom (neutral) may lose on or more of its negatively charged electrons. The remainin part of the atom will then evidently be positively charge It is the better conductors which tend to lose electrons. is very difficult to detach electrons from an insulator.

With these ideas in mind, let us try to explain what happe when (for instance) vulcanite is rubbed with fur or flann Some of the molecules (i.e. groups of atoms) of the fur lo their electrons, which become attached to the surface of t vulcanite. The latter will therefore be negatively charg leaving the fur positively charged. One has simply gain what the other has lost, and so the two *taken together* are st electrically neutral, as we saw in the experiment describ on p. 328 of our earlier book.

We can now give a reasonable explanation of the we known fact that flame has a discharging effect on a char electroscope, vulcanite rod, etc. We must remember th the molecules of a hot gas are in a state of specially viol vibration. It seems likely that, as a result, some of th lose electrons (thereby becoming positively charged), wh others gain them, becoming negatively charged. Th molecules having a charge opposite to that on the vulca will quickly be attracted to it, and will neutralise its char or we may say, those molecules which have lost an elect will combine with the free electrons on the surface of vulcanite, thus discharging it.

B. Electrification by Induction

In our earlier work we made much use of the gold-l electroscope. The diagram (Fig. 33/6) will serve to re it. Notice that the brass disc A, the brass rod BC and gold leaves G, G′ are all in electrical connection with another, but are *insulated* (by suitable material inside cork) from the outer part of the apparatus. If we bea with flannel, it receives a positive charge by friction. T charge is conducted to the leaves, which then repel one ano because they have received 'like' charges. We have char our electroscope positively, by friction.

But we can give it a positive charge in quite another way. Ve bring near it a *negatively* charged rod (vulcanite rubbed ith flannel). The leaves at once diverge. /e may suppose that the vulcanite rod has tracted a positive charge to the brass cap, pelling an equal negative charge to the aves (Fig. 33/7*a*). We now touch the p for a moment. The negative charge capes to earth through the body, and the aves collapse. The positive charge on the p, however, is still 'held' by the negative arge on the vulcanite (Fig. 33/7*b*). We w remove the finger, and then the rod. e positive charge distributes itself over p, rod and leaves, and the latter diverge ce more, this time with a positive charge. e have charged our electroscope by *induction* (Fig. 33/7*c*).

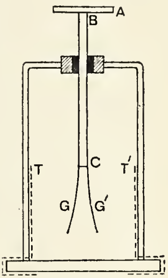


Fig. 33/6

One of the many uses of the electroscope is to find (i) ether a body possesses an electric charge or not; and (ii) the former case, the nature of the charge.

To find whether a body is charged, we bring it near the

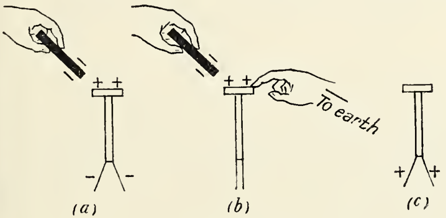


Fig. 33/7

of an uncharged electroscope. If the body is charged, leaves will diverge. (Instead of bringing the body itself, may use a small metal disc mounted on an insulated dle—a *proof plane*—to convey a sample of the charge, if , on the body.)

uppose the body is found to be charged, and we wish to whether the charge is positive or negative. We first

charge the electroscope by induction—say positively, already described. We now gradually bring either the bo itself, or a proof plane which has been in contact with it, n the cap of the instrument. If the leaves diverge more wide the charge was obviously positive. If they gradually colla it was negative.

Faraday's ice-pail experiment. A very instructive series experiments on Induction was carried out by Faraday usi a pewter ice-pail—he used anything that was handy. We repeat his work using a rather tall cocoa-tin or a calorimet

I. The tin is placed on the cap of an electroscope, an metal ball charged (say) positively, and suspended by a s

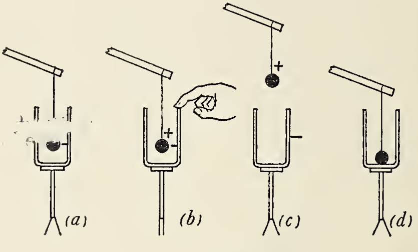


Fig. 33/8

thread, is lowered well inside the tin, without touching sides.

The leaves diverge (Fig. 33/8*a*). On bringing a positi charged glass rod near the electroscope, the divergenc increased, showing that the charge on the electroscop positive. This is what we should expect from our knowle of induction.

On moving the metal ball about, inside the can, but touching it, and not very near the mouth, the leaves are q unaffected. Evidently the magnitude of the induced ch does not depend on the position of the charged body in the hollow vessel.

On withdrawing the ball, the leaves collapse. The when tested is found to have retained its charge.

II. The ball is again introduced, and of course the le

liverge once more, but they collapse when the can is touched vith the finger (Fig. 33/8*b*). The finger and then the ball are ow withdrawn. The leaves diverge to the same extent as efore, but the charge on the electroscope is now found to be egative. The ball still retains its charge (Fig. 33/8*c*).

When the can was touched, the induced positive charge scaped to earth, and only the induced negative charge emained. This must have been *equal* to the induced positive harge, for the leaves diverged to the same extent.

III. We now discharge the electroscope, so as to be exactly here we were at the beginning of the experiment. The ball once more introduced, making the leaves diverge (Fig. 3/8*d*), but the ball is now made to touch the inside of the can. The divergence of the leaves remains unaffected. On ithdrawing the ball it is found to be discharged. The aves still remain apart, and the can and electroscope are w found to be positively charged.

Since the ball was found to be discharged the induced gative charge on the inside of the can must have been equal the positive charge on the ball. Summing up—

from II, induced negative charge = induced positive charge.
from III, induced negative charge = inducing positive charge on ball.

Hence—*when a charged body is introduced into the inside of a sed hollow conductor, each of the induced charges is equal in ignitude to the inducing charge;* and therefore *when the charged ly is made to touch the inside, the entire charge is transferred the outside.*

Now, when we bring a charged body nearer and nearer to electroscope, the leaves diverge increasingly. We might be to think that in this case the induced charge was *less* than the lucing charge, but was increasing as the latter approached. Actually the *total* induced charge is always exactly equal to inducing charge, but not all of it is on the electroscope. ne of it is on the walls of the room, etc. As the charged ly is brought nearer, a larger proportion of the induced rge is concentrated on the electroscope, making it show a ater divergence.

Electric Screening. It seemed to Faraday that as the charg on a hollow conductor was entirely on the outside, the insid should be free from the action of electric forces. He pu this idea to a very severe test. He made a box about 6 f each way and covered the outside of it with conductin material such as tin-foil, wire gauze, etc. Inside the box h had electroscopes and other delicate instruments. The bo was placed on insulating supports, and charged with electric machines to such an extent that an assistant was able t obtain long sparks from the outside, but the instrumen inside were quite unaffected.

A much simpler but quite effective experiment on 'electr screening' can be carried out with an electroscope and lighted taper. The electroscope is charged, and a light taper is placed near the cap. The electroscope is quick discharged (p. 404). It is re-charged, but this time a wi gauze is held between the lighted taper and the cap. Tl leaves now remain open.

Lines of Electric Force. When studying magnetism we ga some attention to *lines of magnetic force*—the lines along whi free north poles would travel under the action of magnet forces. We found that such lines could be obtained by t use of iron filings, or of a compass needle. But we found al that they could be constructed, though very laboriously, l using our knowledge of attractions and repulsions, and of t inverse square law. Let us see how we can make use similar knowledge in electricity [1] to plot ***lines of electr force,*** such a line being *the line along which a free positi charge of electricity would move under the action of electric forc*

To begin with a very simple case, if the 'electric forces' a due to a positive charge P, the lines of electric force will as shown in Fig. 33/9*a*. If P is a charged *sphere*, we m suppose the charge to be concentrated at its centre, and t lines of force will run in the same way (Fig. 33/9*b*).

If the lines of force are due to a *negative* charge P, it is cle that a free positive charge would be *attracted*, so the li point in the opposite direction (Figs. 33/10*a* and 10*b*).

Next we come to the much harder case of when *two* char

[1] It can be shown that the inverse square law also applies to elect static charges.

re concerned, a positive charge at P and an equal negative harge at N (Fig. 33/11), both, of course, *fixed*. If another

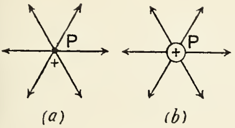


Fig. 33/9

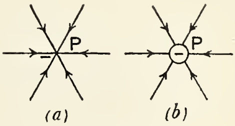


Fig. 33/10

ositive charge, *free to move*, is at p, which way would it travel? It is repelled by P in the direction pa, and attracted by in the direction pc. To represent these forces we must ake the ratio pa/pc equal to $(p\mathrm{N})^2/(p\mathrm{P})^2$ (law of inverse uares). For instance, if $p\mathrm{P} = 1$ nit and $p\mathrm{N} = 2$ units, we should ve to make pa 4 times pc. aving drawn pa and pc of the rrect relative lengths, we comete the parallelogram $pabc$; and is the direction in which p ould *begin* to move. After it d moved a very little way, its rection would alter, because it ould be farther from P and arer to N. Its complete path would be somewhat as own by the dotted line PpN. If a number of such lines

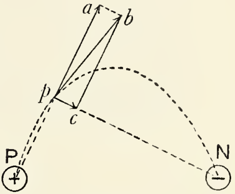


Fig. 33/11

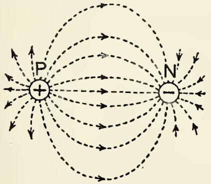


Fig. 33/12

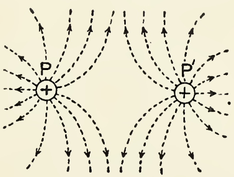


Fig. 33/13

drawn, we obtain Fig. 33/12. On the other hand, if P d P′ are both positive charges, the lines of force run as in g. 33/13.

There are some important characteristics of lines of electri force, which we will briefly summarise.

(1) Starting from a positively charged body, they alway end on one with a negative charge. This may b on a body with a *free* negative charge (Fig. 33/12) Failing this, they end on a body with an *equal induce* negative charge. This charge might be on the wall of the room, the ceiling, etc. In fact, the charges a the two ends of a line of force are always equal an opposite.

(2) They always enter or leave the surface of a conduct at right angles.

(3) They tend to shorten themselves, like cords of stretche elastic. In Fig. 33/12 this would cause P and to close in on one another. We may regard it the reason why 'unlike charges attract one another.'

(4) Lines of force running near to one another, and in th same direction, repel one another. This woul cause P and P′ in Fig. 33/13 to move apart. 'Lik charges repel one another.'

C. **Electrostatic Units**

In the preceding pages we have frequently dealt wi charges of electricity produced by friction. We mig perhaps have described them by such terms as 'strong' 'weak,' but we had no means of accurately *measuring* the because we had no *unit*.

At first sight it seems rather hopeless to have to deci upon a unit of electricity, but we have a key to the problem we know that one charged body will repel another that similarly charged. They repel one another with a certa *force*, and we can measure force in dynes. The force, course, depends on the distance between the two charg and later on we shall find that it varies with the mediu that happens to separate the two charged bodies (usuall but not always, air).

We now have all the material necessary for defining o unit. ***Unit electric charge*** is *such a charge that, if placed vacuo at a distance of* 1 *cm. from a similar charge, it will ca*

ıe latter to be repelled with a force of 1 *dyne.* (The force in ir differs very little indeed from the force *in vacuo.*) We otice a close resemblance to the definition of unit magnetic ɔle on p. 385.

As already mentioned, it can be shown that the force between vo electric charges follows the inverse square law—i.e. it is versely proportional to the square of the distance. Expressed a formula, if two charges q and q' are separated in air [1] by distance of d cm., the force between them is $\frac{qq'}{d^2}$.

Example 1. *Two small spheres carry electric charges of* 20 *and units respectively, and the distance between their centres is* 10 *cm. nd the force of repulsion between them.*

The effect is the same as though the charges were concen- ıted at the centres of the spheres, so the required force = $\frac{\times 30}{10^2}$ = **6 dynes.**

Electric Field. The ***electric field at a given point*** is *the ce in dynes that would be experienced by unit electric charge ıced at that point.*

Example 2. *Find the strength of electric field at a point between the tres of the spheres in Example* 1, *and ɔm. from the centre of the second ere.*

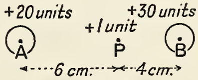


FIG. 33/14

ʾuppose A is the centre of the first sphere, B of the second. P be the point. Then AP = 6 cm. and BP = 4 cm. If we ıgine unit electric charge placed at P, then

$$\text{force due to A} = \frac{20 \times 1}{6^2} = 0{\cdot}56 \text{ dynes.}$$

$$\text{,,} \qquad \text{,, B} = \frac{30 \times 1}{4^2} = 1{\cdot}88 \quad \text{,,}$$

ʾhese forces are in opposite directions, the first acting in direction PB and the second in the direction PA. The ıltant field is therefore one of 1·88 − 0·56 or **1·32 dynes he direction PA.**

[1] If these are separated by some other medium, the force is qq'/Kd^2, re K is the dielectric constant (p. 418).

D. Potential

We all know that if two quantities of water are connecte say by a pipe, there will be a flow from the water at the high level to that at the lower. If there is no difference of lev no flow will take place. It is not a question of *quantity*. hundreds of cases we have water flowing from a lake to t sea (a river-bed in this case taking the place of the pip although the quantity of water in the lake is much less th that in the sea.

Now, just as difference of *level* causes flow of water (a we might add, just as difference of *temperature* causes fl of heat), there is a difference of something which causes fl of electricity. This something is known as *potential*—it difference of potential (often written as 'P.D.') which cau flow of electricity.

Zero Potential. An ordnance map gives the heights various places 'above sea-level.' Sea-level is a very c venient 'zero,' because, although the sea is constantly suffering losses and gains, these are so small compared with the total vast bulk as to make no perceptible difference to the level.

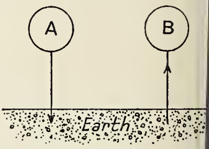


Fig. 33/15

In the same way, the electric charges which are constantly flowing into and out of the earth are so small, compared with the earth's vast store of electricity, as to leave it unaffected for practi purposes. We can no more raise or lower the earth's elect level (i.e. its 'potential') than we can raise or lower the le of the water in the ocean.

For this reason, the earth is said to be at *zero potent* If, when a charged body is connected to earth (A in Fig. 33/1 positive electricity flows from it to the earth, the poten of that body is said to be positive. If positive electric flows in the opposite direction (B in the figure), the poten of the body is negative. If there is no current in eit direction, the potential of the body is zero.

P.D. indicated by Electroscope. We have often used gold-leaf electroscope to indicate the presence of an elec

ıarge, or to tell us which of two charges is the greater. ıdirectly, as we shall see later, the electroscope does give us formation about electric charges, but what it *directly* dicates is difference of potential, as the following experiment ll show.

Place the electroscope on an insulating support—say a slab paraffin wax. Take a piece of copper wire about a foot long d pass it through a piece of rubber, which will serve as an sulating handle. Connect the wire to the cap of the electro- ppe (Fig. 33/16).

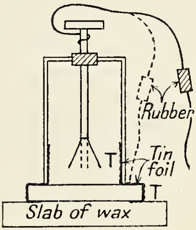


FIG. 33/16

Now charge the electroscope by touch- ; the cap with a proof-plane which s itself been charged by contact with brass disc of an electrophorus (*Junior ysics* p. 321). If necessary, increase charge by repeating the operation h the disc once or twice, until the ves show a good divergence.

Next, holding the copper wire by the ber handle, make its lower end touch tin foil T. The leaves at once col- se. Yet the electroscope cannot have its charge, for the wax slab is insul- ıg it from the earth. We can confirm point (that the electroscope still a charge) by bringing a second electroscope near it. The es of the latter diverge.

Now, when we made the wire touch the tin-foil, the latter ıld acquire the same potential as the cap and leaves. It ns clear, then, that when there is no difference of potential ween leaves and tin-foil, there is no divergence of the es; to put the case the other way round, divergence of leaves indicates a difference of potential between leaves tin-foil.

Ve can vary the experiment by first of all giving a charge he tin-foil (the electroscope being insulated as before). leaves diverge (though they have as yet received no rge). On connecting cap and tin-foil, the leaves collapse efore.

ut although what the electroscope *directly* indicates is ntial difference between leaves and tin-foil, indirectly ɔes indicate the presence of a charge of electricity on the es. For, as ordinarily used (we shall assume this through-

out the following little argument), the tin-foil is earthed-i.e. it is at zero potential. Therefore, since divergen indicates a difference of potential between leaves and ti foil, the leaves themselves must have a potential that is n zero. But to have a potential, they must have received charge[1] (just as to acquire a temperature, a body mu receive heat). Thus divergence of leaves does indicate charge, and the greater the charge, the greater the divergen

This last point is easily proved experimentally. We take t exactly similar electroscopes. We charge the brass plate an electrophorus, and by means of a proof-plane trans what we will call one 'unit' to the first electroscope. To t second, we transfer two or three units. Clearly the seco electroscope has received the greater charge, and it also sho the greater divergence.

Potential of a Conductor. A moment's thought will sati us that the potential at all points of a charged conducto e.g. that shown in Fig. 33/17—must be the same. If,

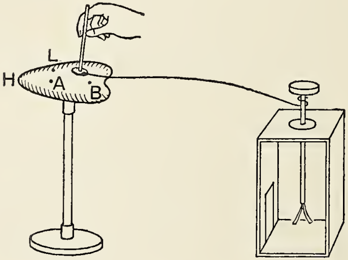


FIG. 33/17

instance, the potential at A were higher than at B, electri would flow from A to B until the potential at both po was the same. We can compare this with the fact that points on a sheet of calm water are at the same level.

To prove the statement experimentally, we may use

[1] Or alternatively they must be in the neighbourhood of some which is not at zero potential—an alternative which in this ca ruled out.

paratus shown in Fig. 33/17. The proof plane is connected a wire with the cap of the (earthed) electroscope. No itter to what part of the conductor we apply the proof-ine, the divergence is the same, and the divergence, as we ve seen, is a measure of the potential.

Potential the Result of Work Done. To raise the level of ter, work has to be done against the force of gravity. We en get an example in a country house, where water may pumped from a well to a tank in the attic.

Correspondingly, when we do work on a charge of elec-city, we raise its 'electric level'—i.e. its potential. Suppose, instance, that at A and B (Fig. 33/18) there are two small lies, one carrying a rge Q, the other a rge q (both positive). ween the two there is, ourse, a force of repul-1. Suppose we bring q a point C, nearer to A. To do so, we have to *do work* inst this force of repulsion, and at C the charge will be o speak at a higher electric level than when it was at B t a higher potential.

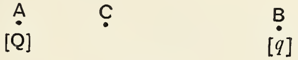


FIG. 33/18

Vhen released, the charged body will tend to move from B. That agrees very well with what we already under-id—that electricity tends to move from a point of higher ne of lower potential.

otential is a quantity which can be accurately measured. tricity is supplied to your house at a certain *voltage*— perhaps: i.e. its potential exceeds that of the earth by volts, the earth's potential being regarded as zero. The is a practical unit of potential. Let us give it a little er attention.

o back to Fig. 33/18, where there is a charge Q at A. pose B is very far removed from A—say a mile—and at here is *unit* charge (defined on p. 410). We begin to ove this charge from B to C.

or much the greater part of the journey we meet with no ceable resistance. As we get rather near to C we begin el the force of repulsion due to the charge at A—a force h can be measured in *dynes*. To overcome this resistance

we have to do work which is measured in *ergs*. The to amount of work which we do in bringing our unit charge to the point C, is the potential at C, and if this amount work is 1 erg, the potential at C is unity.

To be perfectly correct we must make the original distai not a mile, but infinity, and we can now give a formal definiti of the E.S.[1] unit of potential. *In the E.S. system of un if the work done in bringing unit charge from infinity t certain point is one erg, then the potential at that point is uni*

The unit has received no special name—it is simply ' E.S. unit of potential.' The *volt* is $\frac{1}{300}$th part of this unit.

From the definition given above you can probably pr for yourself that the difference of potential between two poi is equal to the work done in moving unit charge from point to the other.

Capacity. Suppose A is a small conductor and B a similar but much larger one, and we give equal charges to each; it can easily be shown by experiment that the potential of A rises more than that of B.

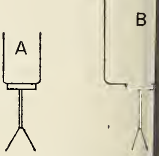


FIG. 33/19

It is more convenient for experimental purposes (though not essential) if A and B are hollow tins which are placed on similar electroscopes (Fig. 33/19). We can t transfer the *whole* of the charge from a proof-plane to th As our 'store' of electricity, we might use the charged b plate of an electrophorus, and make, say, three transfer A and three to B. We give B the first transfer and t alternate them, so that if there is some falling off in amount transferred, one shall not have all the stro charges and the other all the weaker ones.

The 'B' electroscope shows less divergence than the indicating that its potential has not risen so much. Bec it would need a larger charge to make the potential of B as much as that of A, we say that it has a larger elect *capacity*, a term which may be defined as the quantit electricity needed to produce unit increase of poten Thus, if the potential of a conductor rises by V (volts) w

[1] E.S. (also e.s.) = electrostatic.

receives a charge of Q (coulombs), its capacity C would be ÷ V, because this quantity would make its potential rise one volt. Capacity is measured in *farads*. In short, = Q/V, where C is measured in farads, Q in coulombs and in volts. For practical purposes, a unit called the *micro-ad* (=one-millionth of a farad) is commonly employed.

The Condenser. The condenser is an arrangement by means which the capacity of a given conductor may be greatly reased. The underlying principles may be understood m the following experiment.

i) Mount a rectangular zinc plate A on an insulating base, l connect it with an electroscope (at this stage B is not supsed to be present). Charge A by means of an electrophorus, using the leaves of the electroscope to diverge.

Now take a similar zinc plate. Hold it by means of rubber ls to insulate it, and make one vertical edge touch a vertical e of A, but with a little overlap. practical purposes we have *en-ged* A. The electroscope shows a uced divergence.

ii) Take away the supplementary te, thus reducing A to its origi- size. Now bring up B, a plate ilar to A, but earthed. It is nged parallel to A, but is placed that at first only a small portion ts area is opposite A. Slide it ng (guided by a chalk line drawn the table), so that more and e of its area is opposite to A. divergence grows steadily less.

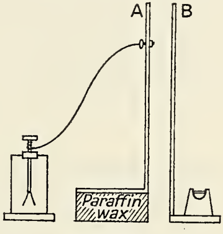


Fig. 33/20

ii) Next bring B nearer and nearer to A. The thinner the r of air between the plates, the less the divergence.

v) Lastly, with A and B at a fixed distance apart, interpose veen them, one at a time, slabs of vulcanite, paraffin wax, glass, hur, etc., taking care not to earth A by accidental contact. l what happens when *water* is used. (Interpose one or two icine bottles containing water, broad side parallel to the plates.)

is known as the *collecting plate*, B as the *condensing e*.

he insulating medium separating the plates is called the *ectric* (air in the early parts of the experiments, later nged as far as possible to vulcanite, paraffin wax, etc.). n our results we may draw the following conclusions.

The capacity of a condenser may be increased by

(i) increasing the area of the collecting plate;
(ii) increasing the effective area of the condensing pla
('effective area' means that portion of the condensi
plate which is opposite the collecting plate);
(iii) reducing the thickness of the dielectric;[1]
(iv) using a dielectric other than air.

More exact experiments have shown that the capacity actually *proportional* to the area of the collecting plate a to the effective area of the condensing plate, and *invers* *proportional* to the thickness of the dielectric.

With regard to (iv), it has been found that the substituti of another dielectric for air (strictly, for vacuum) causes t capacity to be increased in a definite ratio—e.g. usi vulcanite the capacity is increased 3·15 times, paraffin w 2·3 times, and water actually 80 times. This ratio is kno as the *specific inductive capacity*, or *dielectric constant* (usua represented by K).

i.e. *dielectric constant of a given medium*

$$= \frac{\textit{capacity with that medium as dielect}}{\textit{capacity with air as dielectric}}$$

Condensers in Actual Use. The condenser was discove by accident. In 1746 a Dutch physicist, Pieter van M schenbroek, of Leyden, thought he would like to elect some water contained in a bottle. To do it, he attache wire to the prime conductor of an electrical machine, wire dipping into the water. He held the bottle in his ha After the machine had been in action for some time, proceeded to move the wire with his other hand. The res must have been very startling, for he declared that 'he wo not take another such shock for the kingdom of France.'

We can now understand what had happened. Wh very high voltages are concerned water is a conductor. capacity of the water (plus wire) was greatly increased by presence of the man's hand only a few millimetres away thickness of the glass). It would therefore take a m

[1] A very simple example of this is seen when the hand is held nea cap of a charged electroscope. As the hand is brought nearer, the le gradually close in. The hand is, of course, acting as the condenser p

reater charge of electricity before its potential reached that f the prime conductor. When the man took hold of it he ceived this charge through his arms and shoulders, and ems to have been most unwilling to peat the experiment.

This accident gave van Musschenbroek e idea of the Leyden jar, a modified rm of the apparatus that gave him the ock.[1] In its modern form (Fig. 33/21) e have a glass jar coated inside and outle with tin-foil for about half its height, e upper half being covered with shellac rnish to improve the insulation. rough an insulating cover there passes brass rod terminating above in a knob, d below in a chain which makes ntact with the inner tin-foil surface.

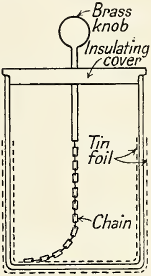


FIG. 33/21

To charge it, the jar is held in the hand (which touches e outside tin-foil) while the knob is in contact with the me conductor of an electrical machine, say a Wimsrst.

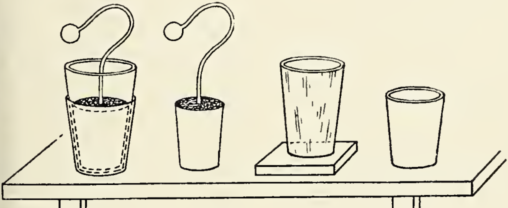


FIG. 33/22

t first sight the Leyden jar looks very unlike the arrangent discussed on p. 417. Comparing Fig. 33/20 with Fig. 21, however, we see that the collector plate A is repre-

It is difficult for us in these days to realise the excitement produced he invention of the Leyden jar. Men used to make their living by ng one round the country, arranging a sort of 'show' in various is and villages, and, of course, making a charge for admission.

sented by the inner tin-foil and the condenser plate B by th outer one. The only difference is that they form cylinde instead of flat surfaces, while instead of air as dielectric w have glass. This has a dielectric constant of about 8, and th capacity of the condenser is increased to that extent.

For experimental purposes, Leyden jars with movabl plates are sometimes used. One is shown in Fig. 33/22 and it can be used to show that the charge is not on the metal surfaces at all, but *on the dielectric.* To show this the condenser is first charged in the ordinary way and earth-connected by placing it on the table. The inner coating is lifted out by means of an ebonite rod, and then touched with the hand. No spark passes. Th glass is removed and placed on a block of paraffin wax. Th outer coating is, of course, connected with earth, so cann contain a charge. The condenser is now re-assembled, the inn metal part being lifted by means of the ebonite rod. Th inner and outer coatings are connected in the usual wa by discharging tongs, when a bright spark passes!

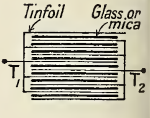


Fig. 33/23

As the charge was not in the metal coatings it must have been on the glass. In fact, if the condenser is again charged and separated as before, it is possible to obtain tiny discharges by holding a lead pencil against the glass.

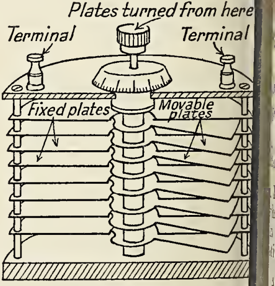


Fig. 33/24

Another form of condenser is shown in Fig. 33/23. Here sheets of glass are coated with tin-foil. Alternate sheets of foil are joined up to a common terminal T_1, and those in between to T_2. The effect is t same as if we had two very large sheets of tin separated glass. Sometimes mica (or in cheaper instruments, wax paper) is used instead of glass, the sheets of tin in this ca not being actually coated on to the mica or paper.

Often, as in a wireless set, we need a condenser of which we n vary the capacity. Here we make use of the fact that the pacity is proportional to the effective area of the plates. g. 33/24 will almost explain itself. We have a fixed set of tal plates, and another set which can be rotated so as to ve in or out of the fixed set. The dielectric in this case is ially air, but in some modern patterns, mica sheets are ached to the plates, and act as the dielectric.

Condensers are used extensively in wireless telegraphy and ephony. They also generally form part of an induction l (p. 501), which in turn has various uses (e.g. for 'coil ition' in a motor car). They play an important part in production of X-rays, and have received a number of er important applications.

Questions

. Gilbert believed that solid substances could be classified *lectrics* and *non-electrics*. What did he mean by these terms? you think his classification was right? If not, explain how ame to make the mistake, and give a better classification.

. Give some account of the modern theory of electrification.

Describe a gold-leaf electroscope. How would you use it how the difference in insulating properties of silk, cotton, oer and mica?

How could you show that equal and opposite charges are luced by friction?

How would you use a gold-leaf electroscope (i) to find ther an insulated metal ball was electrically charged or not, n the former case, to find whether the charge was positive or tive?

A metal can stands on the plate of an uncharged electroscope, a charged metal ball, suspended by a silk thread, is lowered e the can.

scribe and illustrate by diagrams what happens in the wing sequence of independent operations: (*a*) the ball is red until well inside the can and is then withdrawn, (*b*) the is lowered into the can and is allowed to touch it, (*c*) the s lowered into the can as in (*a*), the can is touched momen- with the finger and the ball is then withdrawn.

hat conclusions can be drawn from these experiments?

Lond.

7. Explain why a sheet of metal or gauze is effective in screen-ing a body from the influence of electrostatic forces.

8. Describe how you would charge two insulated metal sphere one positively and the other negatively.

Draw a full-scale diagram showing the lines of force betwe two equally and oppositely charged metal spheres if the radi of each is about 1 cm. and their centres are about 12 cm. apart.

Explain what is meant by a *line of force*, illustrating yo answer by reference to a line in your diagram. *J.M.B.*

9. Define *unit electrostatic charge*.

What is the magnitude of the force between two point charg each of magnitude 20 units, placed 10 cm. apart in air? *J.M.B.*

10. Describe how you would charge a gold-leaf electroscope induction. How would the potential of the leaves vary at ea stage of the process?

Two insulated spheres A and B are placed near, but not touchi each other. B is connected by a wire to the cap of a gold-le electroscope. Explain what happens when (i) A receives positive charge, (ii) the wire is then removed, (iii) the electr scope is then momentarily touched, (iv) the wire connection then restored? *O.C.*

11. You bring your hand near to, but not touching, the c of a charged electroscope; afterwards you withdraw it. St and explain what happens.

12. What do you understand by (a) the potential, (b) t capacity, of a conductor? How is each affected (if at all) the charge on the conductor?

An insulated metal plate is connected to the cap of a gold-l electroscope. State and explain what happens when

(a) an earthed metal plate is placed parallel to and ab 5 cm. from the charged plate;

(b) the earthed plate is then approached nearer the char plate;

(c) a thin sheet of ebonite is then placed between the plat *Lond*

13. Describe an experiment to show that electrostatic cha resides on the outside of a hollow charged insulated conducto

Show how you would use this fact to compare the charges two unequal metal spheres which have been charged when contact and then separated. State, with reasons, which of two spheres you would expect to have the larger charge. *Lo*

14. Two positive electric charges, of 40 and 50 units respectiv are placed 10 cm. apart in air. Calculate the force between th What would the force be if the charges were separated by gl (dielectric constant = 8)?

CHAPTER 34

CHEMICAL EFFECTS OF THE ELECTRIC CURRENT

' we were dealing with our subject in strict historical order, e should now have to learn about the production of the ectric current, which was first obtained about the year 1799. owever, we will leave that point for our next chapter. ıce men knew how to obtain a current, they naturally ed all sorts of experiments with it. They soon found, for stance, that *in certain cases* substances can be decomposed dissolving them in water and then passing an electric rrent through the solution. A very straightforward case that of hydrochloric acid (Fig. 34/1). A and C are carbon *ctrodes* in a glass jar containing the dilute acid. The rrent enters at the *anode* A d leaves by the *cathode* C. ydrogen collects in the test-be T_2, over the cathode, t very little chlorine is col-ted in T_1, because the gas very soluble. The process known as *electrolysis*, and vessel in which it is car-l out is called an *electro-c cell* or *voltameter*.

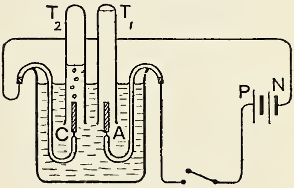


FIG. 34/1

A solution which is capable of undergoing electrolysis is own as an *electrolyte*. In some cases a substance acts as electrolyte when in a state of fusion. Sodium chloride is example.

)ther cases previously studied—sodium chloride (in solu-ı), copper sulphate, and 'water' (actually dilute sulphuric l)—will be reconsidered later in the chapter.

aws of Electrolysis. The subject of electrolysis was estigated by Michael Faraday. By careful measuring (in case of gases) or weighing (solids) he found the exact ntities of the substances produced by electrolysis, and wed that these quantities were proportional to

(i) the strength of the current and
(ii) the time during which the current was passed.

Multiplying (i) and (ii) together we have a measure of th *quantity of electricity* that has passed through the solution and the results are summed up in Faraday's ***First Law o Electrolysis***, which states that *when a substance undergoes electrolysis, the weights of the products liberated at the electrodes are proportional to the quantity of electricity passed.*

A method of illustrating this law was described in our earlie book, and here we shall content ourselves with a brief résumé, and a sketch of the apparatus (Fig. 34/2).

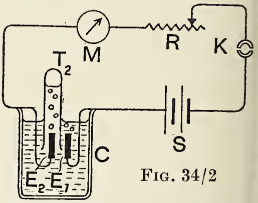


FIG. 34/2

The large beaker C contains very dilute sulphuric acid. Hydrogen is collected in T_2, and it is found that the volume (and therefore the weight) is proportional to (i) the time, and (ii) the strength of the current. The latter quantity can be altered when required by adjusting the re sistance R.

Let us next consider the kind of experiment which led u to Faraday's Second Law. He prepared solutions of differen electrolytes, and arranging them in series, passed the sam current for the same time through each. Suppose, fo instance (Fig. 34/3), that A is a solution of copper sulphat and B of silver nitrate, while C consists of water acidified wit sulphuric acid. When the circuit is completed we find tha copper is deposited on the cathode of A, and silver on tha of B. At the cathode of C (as seen in the previous experimen hydrogen is set free, and can be collected in a graduated tub The reactions at the anodes of A and B are somewhat com plicated, and for the sake of simplicity we will not consid them now. In the case of C, oxygen is given off at the anod and can be collected in another graduated tube.

At the beginning of the experiment the cathodes of A an B are weighed. The current is passed for a certain time, sa half an hour, and the cathodes are weighed again. By su traction, we find (i) the weight of copper deposited on th cathode of A and (ii) the weight of silver deposited on that of

The volume of hydrogen is observed, and after correcting his for temperature and pressure we can (knowing its density) lculate its weight. Similarly, we can find the weight of xygen in the other tube. Let h, o, c and s (gm.) be the weights hydrogen, oxygen, copper and silver respectively. Faraday und a very curious relationship between the weights, viz. $: o : c : s = 1 : 8 : 31{\cdot}8 : 108$. But why is the relationship rious?

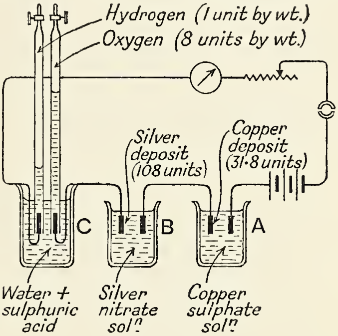


Fig. 34/3

If you look at a table atomic weights, you ll find that those of e elements concerned e respectively 1, 16, ·6 and 108. Further, e *chemical equivalent* an element is A ÷ V, ere A is its atomic ight and V is its lency.[1] The valencies the four elements der discussion are pectively 1, 2, 2 and Thus their chemical uivalents are—hydrogen $1 \div 1 = 1$, oxygen $16 \div 2 = 8$, pper $63{\cdot}6 \div 2 = 31{\cdot}8$ and silver $108 \div 1 = 108$.

Going back a few lines to the statement $h : o : c : s =$ $8 : 31{\cdot}8 : 108$, we see that *the weights of the elements rated are proportional to their respective chemical equivants.*

)ther experiments gave similar results, and so he was to his ***Second Law of Electrolysis***:—*If the same quantity*

[1] Briefly, the *valency* of an element is the number of atoms of rogen which one atom of the element will combine with, or displace. s one atom of oxygen combines with two atoms of hydrogen), so the valency of oxygen = 2. We may regard copper sulphate, O_4, as being formed by the replacement of *two* atoms of hydrogen ulphuric acid (H_2SO_4) by one atom of copper; so the valency of ɔer = 2. A comparison of the formula of silver nitrate, $AgNO_3$, that of nitric acid, HNO_3, shows that the valency of silver is one. he law applies not only to elements but to 'compound radicals' as NH_4, SO_4, NO_3, etc. In practice these nearly always undergo ıer changes on liberation.

of electricity is passed through different electrolytes, the masses o the different substances liberated at the electrodes are proportiona to their chemical equivalents.

The experiment just described evidently takes a long tim to carry out. It is worth noticing, however, that we ca quickly obtain an example of the law from the fact that th volume of the hydrogen in C is just twice that of the oxyger For it is known that two volumes of hydrogen *combine* wit one volume of oxygen to form water. Thus two volumes c hydrogen are *equivalent* to one of oxygen, and so in the proces of electrolysis these gases have been liberated in quantitie proportional to their chemical equivalents.

Electrochemical equivalent. In what follows we shall b concerned with *quantity of electricity*, so let us be clear on th question of how this is measured.

On p. 457 we shall see that a current could be measured b its magnetic effect. In this way we obtain the 'electro magnetic unit of current,' one-tenth of which is the amper *The quantity of electricity conveyed by a current of one ampe in one second is known as the* ***coulomb.***

Now, we have just seen that a quantity of electricit which would liberate 1 gm. of hydrogen would also libera 8 gm. of oxygen, or 31·8 gm. of copper, or 108 gm. of silve these numbers being the respective equivalent weigh expressed in grams. The equivalent weight so expressed known as the *gram-equivalent*. Thus the quantity of electricit needed to liberate one gram-equivalent of any substan is constant. This quantity has been found to be 96,5(coulombs.

Evidently, 1 coulomb would liberate the 1/96,500th pa of a gram-equivalent. For copper this quantity would l $31{\cdot}8 \div 96{,}500 = 0{\cdot}000329$ gm. per coulomb, for silv $108 \div 96{,}500 = 0{\cdot}00112$, for hydrogen $1 \div 96{,}500$ $0{\cdot}0000105$, and so on (grams per coulomb in each cas These quantities are known as electrochemical equivalents, i the ***electrochemical equivalent of an element*** is *the numb of grams of that element liberated by one coulomb.* It woul of course, have been equally correct if instead of sayi 'liberated by one coulomb' we had said 'liberated by a curre of one ampere flowing for one second.'

Notice that electrochemical equivalents are *proportional* to
ıemical equivalents. For if e_1 and e_2 are the electrochemical
uivalents of two elements whose chemical equivalents are
spectively E_1 and E_2, then $\frac{e_1}{e_2} = \frac{E_1 \div 96{,}500}{E_2 \div 96{,}500} = \frac{E_1}{E_2}$.

Notice, too, that from the rate at which a metal is deposited
electrolysis, we can derive a new definition of 'ampere,' and
e which will be of much more practical use than the 'electro-
ıgnetic' definition given on p. 457. Thus by careful
periment it has been found that a current of 1 ampere,
ssing through a suitable solution of a silver salt, causes
ver to be deposited at the rate of 0·001118 gm. per sec.,[1]
d so an ***ampere*** is now often defined as *that current which
passed through a silver voltameter, will cause silver to be
ɔosited at the rate of* 0·001118 *gm. per sec.*

Example **1.** *If the atomic weight of aluminium is* 27 *and its
ency* 3, *what is its electrochemical equivalent?*

Chemical equivalent = 27 ÷ 3 = 9

∴ 96,500 coulombs will liberate 9 gm.

∴ 1 coulomb ,, ,, 9 ÷ 96,500 = 0·0000933 gm.

.e. electro-chemical equivalent = **0·0000933 gm. per coulomb.**

A useful equation. Suppose a current of c amperes is passed
t seconds through an electrolyte, causing an element of
ɛtro-chemical equivalent z to be liberated.

Then wt. liberated by 1 ampere in 1 second $= z$ gm.

∴ ,, ,, ,, c amps ,, 1 ,, $= z \times c$ gm.

∴ ,, ,, ,, c ,, ,, t ,, $= z \times c \times t$,,

ing this weight w, we have the equation $w = ctz$, which
shall often find useful.

esting an ammeter. Let us see how we could use our
wledge of electro-chemical equivalents to check the
lings of an ammeter.

[1] It is from this experimental number that the number 96,500
iously given is derived. For to liberate 107·88 gm. of silver (exact
ɘ of gram-equivalent) we need 107·88 ÷ 0·001118 = 96,500
ɔmbs.

A rectangular strip of copper about 4 in. × 2 in. is fastene by nails or screws to a wooden bar measuring about 4 in. × $\frac{3}{4}$ in. × $\frac{1}{2}$ in. as shown in Fig. 34/4*b*. A binding screw i inserted at S_1. Two other strips are attached to woode bars in the same way, and the three are suspended in a glas jar or large beaker (J in Fig. 34/4*a*). S_1 and S_2, the bindin screws of the outer strips, are joined by a piece of coppe wire W. A circuit will finally be completed as indicate where B is a battery consisting of two 2-volt accumulato in series, K is a key, R an adjustable resistance, and A th ammeter whose readings are being tested. The centr copper strip is to be a cathode, the two outer ones bein connected to form a single anode.

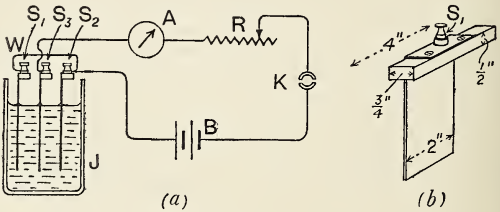


Fig. 34/4

The cathode (with its wooden attachment) is cleaned wi emery paper, washed (first with water and then with methylat spirit) and dried by waving it about in the hot air over bunsen burner. It is then carefully weighed and replac in position in the jar. The latter is about three-parts fill with a strong solution of copper sulphate to which a few c of strong sulphuric acid have been added. The time (minut and seconds) is noted just as the switch is closed, and t resistance is adjusted as quickly as possible so that A sh read 1 amp. This reading is observed again at fairly freque intervals, and R is adjusted if necessary to keep it to ampere.

At the end of half an hour the switch is opened, and t cathode is removed, washed, dried and weighed as befo

ie result is then worked out as follows:—

Wt. of cathode before expt. . . .	32·348 gm.
,, ,, after ,, . . .	32·944 ,,
∴ wt. of copper deposited . . .	0·596 ,,

e current as measured by the ammeter is 1 amp. Suppose *real* strength is c amps. It was passed for $\frac{1}{2}$ hr. $= 1800$ sec.

Γhe electro-chemical equivalent of copper is 0·0003294.

∴ from $w = ctz$ we have

$$0{\cdot}596 = c \times 1800 \times 0{\cdot}0003294, \text{ giving } c = 1{\cdot}005.$$

:t would, of course, be laborious in the extreme to make a nplete check of all the readings of the ammeter by the thod just described. We could, however, check a few them, including the highest and lowest, and express our ılts in graphical form, marking ammeter readings horitally, and errors vertically. Our graph would then tell what correction to apply for any given reading. We uld be said to have *calibrated* the instrument.

t may be mentioned that, in the most exact work, a silver ameter is employed. Very good results, however, can obtained with a copper voltameter, as in the experiment described. A source of error is the fact that unless the osit of copper is dried very gently, it tends to oxidise.

etermination of Electro-chemical Equivalents. To find the tro-chemical equivalent of a metal such as copper, we ıld proceed exactly as described in the last paragraph. re, we assumed the value of the electro-chemical equivalent, found the strength of the current. Conversely, if we w the strength of the current (i.e. if we may assume that ammeter is correct) we can find the value of the electronical equivalent.

cample 2. *In an experiment to find the electrochemical equivalent pper, a current of* 0·8 *amp. was passed for* 40 *minutes through pper voltameter, and caused the cathode to increase in weight* 28·731 *to* 29·363 *gm. Find the value of the electrochemical valent.*

t. of copper deposited $= 29{\cdot}363 - 28{\cdot}731 = 0{\cdot}632$ gm.

the equation $w = ctz$, we have $w = 0{\cdot}632$, $c = 0{\cdot}8$ and seconds) $= 40 \times 60 = 2400$.

$$0{\cdot}632 = 0{\cdot}8 \times 2400 \times z \text{ which gives } z = \mathbf{0{\cdot}000329.}$$

In the following example, the unknown quantity is t.

Example 3. *A metal disc,* 6 *cm. diameter and* 1 *mm. thick,* *to be coated with a film of copper* 0·01 *mm. thick by electrolysi* *What time will be required if a current of* 2 *amp. is employe* *(The electro-chemical equivalent of copper is* 0·000334 *gm. p* *coulomb; the density of copper is* 8·8 *gm. per c.c.)* Lond.*

We must first find the weight of copper to be deposited.

Area of disc (2 sides) $= 2 \times \pi r^2 = 2 \times \frac{22}{7} \times 3^2 = 56{\cdot}6$ sq. cm

Area of rim $= 6 \times \frac{22}{7} \times 0{\cdot}1 = 1{\cdot}9$ sq. cm.

Total area $= 56{\cdot}6 + 1{\cdot}9 = 58{\cdot}5$ sq. cm.

This is to be coated to a depth of 0·01 mm. or 0·001 cm.

$\therefore$ vol. of copper to be deposited $= 58{\cdot}5 \times 0{\cdot}001 = 0{\cdot}0585$ c

$\therefore$ wt. of copper $= 0{\cdot}0585 \times 8{\cdot}8 = 0{\cdot}515$ gm.

In the equation $w = ctz$

we have $w = 0{\cdot}515$, $c = 2$, $z = 0{\cdot}000334$ and $t = ?$

$$\therefore \quad t = \frac{w}{cz} = \frac{0{\cdot}515}{2 \times 0{\cdot}000334} = 771 \text{ sec.} = \mathbf{12\ min.\ 51\ sec.}$$

The Ionic Theory. It must not be thought that electroly is possible with *any* solution. If, for instance, we were place an anode and cathode in a solution of sugar, nothi would happen—no current would flow. Electrolytes, fact, are limited to the three classes of substances known the chemist as *acids*, *bases* and *salts*. For simplicity, let consider the case of the substance mentioned at the beginni of this chapter—hydrochloric acid, which is a solution of t gas hydrogen chloride.

Chemists give hydrogen chloride the *formula* HCl, meani that the smallest particle of it that can exist—the *molecule* consists of an atom of hydrogen, H, combined with an at of chlorine, Cl. There is good reason to believe that wh hydrogen chloride dissolves in water it *ionises*, which me that it splits up into a positively charged hydrogen atom a a negatively charged chlorine atom, thus: $HCl = H^+ + C$ These charged atoms are known as *ions*.

The charges are produced by the passage of an *elect* (p. 402) from the hydrogen atom to the chlorine atom. Y will remember that the electron is a particle of negative el tricity. When the chlorine atom, previously neutral, ga

ıch a particle, it naturally acquires a negative charge, while ıe hydrogen atom, *losing* negative electricity, acquires a ɔsitive charge. Instead of $HCl = H^+ + Cl^-$, we might have ritten $HCl = H^{-e} + Cl^e$, e standing for an electron.

Hydrogen *ion* (H^{-e} or H^+) has very different properties from ɩe hydrogen *atom* (simply H). Similarly chlorine ion (Cl^e or $^-$) is very different from ordinary chlorine. For instance, does not bleach litmus, as we can sily show by dipping litmus paper to dilute hydrochloric acid; and it ɪes not *smell* like chlorine. In ɛt, it has no smell at all.

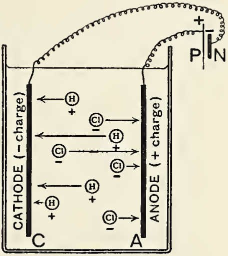


Fig. 34/5

Suppose now we take some hydroloric acid, containing hydrogen ıs and chlorine ions, and into it t a positively charged plate A and negatively charged one C—the *ctrodes* of which we have so often ɔken. In the absence of ions ɛhing would happen. There uld simply be a gap in the circuit between A and C (Fig. 34/5). vould have acquired the (positive) potential of P and C the gative) potential of N, and there the matter would rest.

But in the presence of ions something quite different happens. ɛ chlorine ions, Cl^e, being negatively charged, are attracted ɛhe positive plate (the anode). There they discharge their ɛtrons, becoming ordinary chlorine atoms ($Cl^e = Cl + e$, $2Cl^e = Cl_2 + 2e$). We may suppose that the electrons s through the connecting wires and battery to the cathode. at happens to them there?

ust as the negatively charged chlorine ions are attracted to anode, the positively charged hydrogen ions (H^+ or H^{-e}) attracted to the cathode, which is negatively charged ıuse of the presence on it of the electrons mentioned above those originally derived from chlorine ions). Each rogen ion as it reaches the cathode takes up an electron, ɔming ordinary hydrogen ($H^{-e} + e = H$, or $2H^{-e} +$ $= H_2$). Thus we have a continuous flow of electrons, *ide* the liquid *from* the cathode, and *inside* the liquid ɛre the electrons are carried by chlorine atoms) *towards* the

cathode. As the electrons represent negative electricity, the 'direction of the current' (i.e. of positive electricity) is in the opposite direction.

Some atoms (or groups of atoms) carry more than one electron. Sulphuric acid for instance, H_2SO_4, is electrically neutral. But when it is dissolved in water, each hydrogen atom gives rise to the ions H^+, H^+ (or H^{-e}, H^{-e}), and therefore the sulphate group must give rise to SO_4^{--}, or SO_4^{2e}, i.e. the sulphate ion must carry *two* electrons. Again, when copper sulphate, $CuSO_4$, ionises, the copper ion must contain two positive charges to balance the two negative charges of the SO_4 group, i.e. copper sulphate ionises as Cu^{++}, SO_4^{--}, or Cu^{-2e}, SO_4^{2e}. We soon begin to see that *the number of electrons carried by an atom or group corresponds to its valency.*

To turn to another point, suppose we were to electrolyse a solution containing the mixed salts copper nitrate, $Cu(NO_3)_2$, and silver nitrate, $AgNO_3$. Would copper be deposited at the cathode, or silver, or both?

It is found that less electrical energy is required to discharge the silver ions than the copper ions. As a result, the silver is deposited first, and later, the copper. This illustrates an important principle—that *there is a certain order of preference in which the metals are deposited.* To mention only a few of them, the order is silver, copper, hydrogen, sodium (hydrogen is not strictly speaking a metal, but resembles one in its chemical behaviour). In a similar way, there is an order of preference for the *anions*—the elements or groups which are discharged at the anode. We shall be chiefly concerned with the anions chloride, Cl^-, hydroxide, OH^-, and sulphate, $SO_4^=$, and under ordinary conditions of working we shall find they are discharged in that order—chloride most easily, then hydroxide, then sulphate.

Important cases of electrolysis. We shall now consider a few cases of electrolysis in the light of the ionic theory just discussed, beginning with *Water.* (For this experiment, the apparatus of Fig. 34/1 may be used, except that the electrodes must be of platinum, not carbon.)

If pure water is used, the action is slow in the extreme because (except to the extent of one molecule in about 5[illegible] *millions*) water does not undergo ionisation.

If however a little sulphuric acid is added, hydrogen and ygen are produced at the cathode and anode respectively, o volumes of the former to one of the latter. There is no ange in the amount of sulphuric acid. Let us consider refully what has happened.

The sulphuric acid present is completely ionised ($H_2SO_4 =$ $^+ + SO_4^=$, or $H_2SO_4 = 2H^{-e} + SO_4^{2e}$). The ions thus oduced travel to the electrodes, hydrogen ions to the cathode d sulphate ions to the anode.

To an extremely slight extent, water is also ionised $_2O \rightarrow H^+ + OH^-$), and the hydrogen and hydroxide ions ve towards cathode and anode respectively.

At the cathode there is no complication. The only ions sent are hydrogen ions, and these are discharged with the duction of ordinary hydrogen. We may write $4H^{-e} +$ $\rightarrow 4H \rightarrow 2H_2$, or simply $4H^+ \rightarrow 4H \rightarrow 2H_2$.

At the anode we have numerous sulphate ions, $SO_4^=$ or ^{2e}, and a relatively very small number of hydroxide s OH^- or OH^e. Because of the 'preferential' principle ady mentioned, however, it is the hydroxide ions, not the hate ions, which are discharged. Corresponding to $^{-e}$ at the cathode, we must deal with $4OH^e$, and we get $H^e \rightarrow 4OH + 4e \rightarrow 2H_2O + O_2 + 4e$, or simply $4OH^- \rightarrow$ $H \rightarrow 2H_2O + O_2$.

hus for every two molecules of hydrogen produced, $2H_2$, have one molecule of oxygen O_2, and by Avogadro's Law volumes will be in this same ratio $2 : 1$. The sulphate with a corresponding number of hydrogen ions remain ischarged, i.e. the amount of sulphuric acid in the solution ains unchanged.

'e have still to deal with one pretty obvious question. iere are, relatively, so few hydroxide ions present, how can serve to discharge sufficient electrons to maintain the ent?

ie answer is that as fast as hydroxide ions are discharged, are replaced by other hydroxide ions derived from the ation of fresh molecules of water. Thus though the ber of such ions is never large, the supply never runs out. the ions provided by the sulphuric acid which 'ferry' electrons from one electrode to the other—which carry

the current in fact—but it is those from the water which a
concerned in the discharge at the anode, while at the catho
all ions are of the same sort, and no problem arises.

Copper sulphate. (i) *Using platinum electrodes.* Suitab
apparatus for the experiment is shown in Fig. 34/7, a tes
tube T being supported over the anode by a clamp.

A gas collects in T. On examination (glowing splint tes
it proves to be oxygen. The anode remains unchanged.

The cathode becomes coated with copper,[1] but no bubbl
of gas are seen.

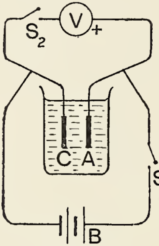


FIG. 34/6

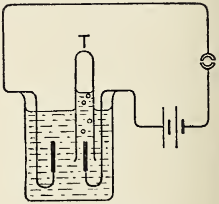


FIG. 34/7

Gradually, the blue colour of the solution becomes l
intense.

Explanation. Copper sulphate and water both ionise, t
latter only to a very slight extent. Thus, the cations pres
are Cu^{++} and H^+, the anions being $SO_4^=$ and OH^-.

At the cathode it is the copper ion which is discharged
preference to the hydrogen ion. It becomes ordinary copp
which is deposited ($Cu^{-2e} + 2e \rightarrow Cu$).

At the anode, we have the case already discussed in c
nection with water + sulphuric acid. Hydroxide ion
discharged, giving rise to oxygen.

Of the ions originally present, Cu^{++}, SO_4^{--}, (2)H^+ a
(2)OH^-, the first and last are steadily removed, leaving
second and third, which are the ions of sulphuric acid.

(ii) *Using copper electrodes.* If the apparatus of Fig. 3
happens to be set up, it will serve admirably. If not,

[1] Readily removed by means of nitric acid.

nplified form of Fig. 34/8 gives quite satisfactory results. In :her case the anode and cathode should each be carefully eaned, washed and dried before and after the experiment, iich should proceed for about half an hour.

No gases are evolved, but a pinkish deposit of copper is en on the cathode. On washing, and gently drying, the thode is found to have gained weight and the anode to have t an equal amount.[1]

Explanation. The action at the cathode is the same as that eady discussed. At the anode ere are three possible actions: discharge of OH^- ions, (b) charge of $SO_4^{=}$ ions, (c) con-sion of copper, Cu, into copper , Cu^{++}, i.e. gradual solution the anode. Of these three, it he last which requires the least ount of energy, and which refore takes place.

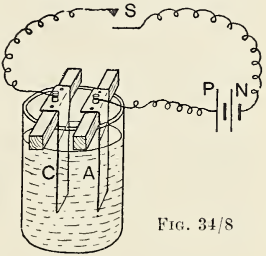


Fig. 34/8

Thus, in the final result, copper steadily removed from the ode and added at an equal rate to the cathode, the amount of per sulphate in solution remaining constant. For all ctical purposes, the effect is as though copper 'travelled' n anode to cathode.

ractical Applications. Practical applications of electro-s are very numerous. We have just seen, for instance, t copper may be deposited on a copper cathode, using a per anode and a bath of copper sulphate. On a large e this principle is used for the preparation of copper of a 1 degree of purity, for which there is much demand in the trical industry.

n our earlier book (Chapter 38) we explained how trolysis may be used to obtain an exact replica of an ect, such as a medal. Gramophone records are also pro-ed by a somewhat similar process (p. 322).

sing a solution of *silver* salt in the bath, and a silver de, we obtain a deposit of silver. This is the basis of the

[1] Owing to the presence of impurities, the anode may be found to lost a little more weight than the cathode has gained.

important process of silver plating. In chromium plati (taps, car radiators, etc.) the bath contains a solution chromic acid (from which the chromium deposit on t cathode is obtained); the anode in this case, however, d not consist of metallic chromium but of lead alloyed wi antimony.

Reversal of Chemical Action. If we try to electrolyse dil sulphuric acid, using a single Daniell cell, the results a practically nil. A few bubbles of oxygen and hydrog collect on the anode and cathode respectively, but after few seconds all action stops.

To understand the situation we must first consider t term *electromotive force* (E.M.F.). In a Daniel cell (or a other form of voltaic cell) a difference of potential is set between the two plates in contact with the acid, and t difference of potential is regarded as the force moving t electricity—the electromotive force. It is measured in vol and in the case of the Daniell cell is equal to about volts.

Now, when we try to use a Daniell cell for the electroly of dilute sulphuric acid, we first get a few oxygen bubb and a few hydrogen bubbles, as already noted. We m regard these bubbles as two *plates* of a voltaic cell, a plate oxygen and a plate of hydrogen, and between these pla there is a difference of potential which tends to set u current in the opposite direction to that produced by Daniell cell. We have, in fact, what is called a *back E.M* This back E.M.F. rises, and as soon as it reaches 1·1 volts Daniell cell can no longer send a current round the circuit.

The fact that 'plates' of oxygen and hydrogen are able set up a back E.M.F. is easily shown by the follow experiment.

A battery B, consisting preferably of two accumulat in series, is connected up with a 'water voltameter' (actu dilute sulphuric acid) as shown in Fig. 34/6. The circuit be completed or broken by means of the switch S_1. platinum plates, C and A, can also be connected, throug second switch S_2, with a high resistance voltmeter V, positive plate of the battery being connected with the posit terminal of the voltmeter.

S_2 being open, we close S_1 and allow electrolysis to proceed ɔr a few seconds, so that oxygen collects on A and hydrogen n C. We now open S_1 and close S_2. The voltmeter gives a eading of about 1·5 volts, but this soon falls to zero. Evi-ently the voltameter has for a very short time acted as a cell, iving a current in the opposite direction to that of the current om B. As it does so, the oxygen and hydrogen bubbles ecombine forming water, but the quantity of these gases is so nall that the action is very quickly over.

Clearly, for electrolysis to be continued, we must use a ttery of greater E.M.F. than the 'back E.M.F.' (of about 5 volts) set up by the oxygen and hydrogen. We could, for stance, use two Daniell cells in series (giving about 2·2 volts).

But perhaps a more important point is this. Our experi-ent shows that it is possible,—

(i) by means of electrolysis to produce a certain chemical change, in this case the decomposition of water into hydrogen and oxygen;

(ii) *by reversal of the chemical change* (in this case allowing hydrogen and oxygen to recombine forming water) to produce *a current.*

It is true that the brief current we obtained from hydrogen d oxygen could be of no practical use, but perhaps if we used ıer substances we might obtain a useful continuous current.

Let us repeat our experiment with one difference—for our ctrodes we use strips of lead foil.

With S_1 closed and S_2 open, the anode gradually becomes rk brown, owing to the formation of lead peroxide, PbO_2. ygen that was previously given off at the (platinum) anode ıow combining with the lead. At the cathode most of the drogen is given off as before, but a little of it may be spent reducing (to lead) a thin film of lead oxide with which d foil is usually coated.

On opening S_1 and closing S_2, the voltmeter records about volts, and this does not fall so rapidly as before.[1] When E.M.F. has fallen to zero, or near it, we can restore it by

[1] If *large* pieces of foil have been used, about 8 in. × 6 in., close ether in the dilute acid, an electric bell may be put in the place of voltmeter, and can be made to ring when S_2 is closed. The pieces oil should be screwed to a separating strip of wood about ½ in. wide.

opening S_2 and closing S_1 for a short time, and so on again ar again. We have really made a simple *accumulator* or *storage ce*

In a 'real' accumulator substantial lead plates are use with hollowed-out squares, slots, etc., into which red lead compressed. On charging, this is converted into lead p oxide by the oxygen produced at the anode, and into a spon form of lead at the cathode (where hydrogen is produced).

$$\textit{Anode.}\quad Pb_3O_4 + 2O = 3PbO_2$$
$$\textit{Cathode.}\quad Pb_3O_4 + 8H = 3Pb + 4H_2O.$$

The lead peroxide is the positive plate of the cell, while t lead is the negative.

From this point the accumulator may be alternat discharged and charged for an indefinite number of tim We will not discuss the chemical changes that take pla except to say that (i) at *discharge*, the lead peroxide and le mentioned in the above equations are both converted in lead sulphate, $PbSO_4$, some of the sulphuric acid being us up in the process. When the conversion is complete, further discharge is possible because both plates are cover with the same material; (ii) at *charge*, the lead sulphate on t anode is converted into lead peroxide, PbO_2, while that on t cathode is reduced to lead. Thus the accumulator is or more ready for discharge.

An accumulator will have a longer life and give better serv if the following points are kept in mind.

When new, the metal terminals, etc., should be smear with vaseline, to prevent corrosion by accidental contact w the acid electrolyte. The outside should be kept dry prevent leakage of current. Water is steadily lost by evapo tion, so the accumulator should be 'topped up' every week so, distilled water being used (ordinary water may cont metal salts in solution, which will give rise to local action).

The cell should not be allowed to give a current greater th that stated on the instructions. Otherwise, too much hea generated, and the plates are liable to buckle, causing paste filling to fall out. For the same reason, the cell sho never be short-circuited. From time to time the spec gravity of the electrolyte should be tested with a suita hydrometer. If it has fallen below 1·17, it is time

cumulator was re-charged. (As already mentioned, sulphuric id is used up during discharge, causing the specific gravity fall.) Another useful instrument is the voltmeter, which ould indicate a voltage of not less than 1·85.

Questions

1. State Faraday's laws of electrolysis and explain what is eant by *electro-chemical equivalent*. Describe, with the aid of liagram, a copper voltameter and explain how it works.

A current of 0·5 amp. is passed through a copper voltameter. nd the weight of copper deposited in 15 minutes. (The ctro-chemical equivalent of copper = 0·00033 gm. per ulomb.)

2. State Faraday's laws of electrolysis.

How could the correctness of the 0·5 amp. reading of an am-ter be tested by means of a copper voltameter?

If in such an experiment 0·18 gm. of copper is deposited on one the electrodes in 20 min. what is the error of the 0·5 amp. ding? (Elec.-chem. equiv. of Cu = 0·000329 gm./coulomb).

Dur.

3. Calculate the current which, flowing for 20 minutes in a pper voltameter, deposits 0·48 gm. of copper. (Electro-mical equivalent of copper is 0·000329 gm. per coulomb).

w = c t z

*Camb.**

4. What is meant by the *electro-chemical equivalent* of an nent? Describe an experiment to determine its value for per, and show how you would calculate the result.

A current of 2 amperes was passed for half an hour through a per voltameter. How much copper was deposited on the hode, if it is known that the electro-chemical equivalent of per is 0·000329 gm. per coulomb? *Dur.*

5. Explain why an electric current flows readily through an eous solution of salt, but not through an aqueous solution ugar.

6. A current is passed through three voltameters connected series. They contain respectively (*a*) dilute sulphuric acid 1 platinum electrodes, (*b*) silver nitrate solution with silver trodes, (*c*) sodium chloride solution with carbon electrodes. cribe the changes which take place at the six electrodes and e the relation between the quantity of oxygen liberated in voltameter and the quantity of metal deposited in another.

J.M.B.

Calculate the current required to silver plate a metal tray m. by 43 cm., on one side in 10 hours, with a coating 0·1 mm. k. Assume the electro-chemical equivalent of silver to be 1118 gm. per coulomb and its density to be 10·5 gm. per c.c.

*Lond.**

8. It is required to deposit electrolytically a film of silver thickness 0·1 mm. on a spoon of surface area 20 sq. cm. If t current used is 0·1 amp., how long will the process take?

(Electro-chemical equivalent of silver 0·00112 gm. per couloml density of silver 10·5 gm. per c.c.) *Camb.**

9. How long would it take to give a coating of copper, 0· cm. thick, to a metal article of surface area 27·0 sq. cm., using current of 0·5 amp.? Take the density of copper to be 8·8 g per c.c. and its electro-chemical equivalent to be 0·00033 g per coulomb. *C.W.B.**

10. Describe in detail how you would make a replica in metal copper of one side of a medal by an electrolytic process.

In order to deposit 15 gm. of silver on a teapot, a current 0·5 amp. was found to be suitable. For what length of ti would it be necessary for the current to flow? (Electro-chemi equivalent of silver = 0·00112 gm./coulomb.) *Dur.*

11. Define *coulomb*, *ampere*, *electro-chemical equivalent*, a state the laws governing the liberation of elements by electroly

A current of 2 amp. is passed for 12 min. through a wa voltameter, and 280 c.c. of hydrogen measured at N.T.P. liberated. If the chemical equivalent of copper is 31·5 a 11·2 litres of hydrogen at N.T.P. weigh 1 gm., calculate t electro-chemical equivalents of hydrogen and copper. *O.C.*

12. A current of 2 amp. is passed for 5 min. through a sil voltameter and 0·672 gm. of silver are deposited. If t chemical equivalents of silver and gold are 108 and 65 respective calculate the electrochemical equivalent of gold. *O.C.*

13. While testing the correctness of the 0·1 amp. reading an ammeter, it was found that 0·4070 gm. of silver was deposit in 1 hour. Calculate the error, given that electrochemi equivalent of silver = 0·001118.

14. A current is passed for some time through two vol meters in series, the first containing copper sulphate soluti the second dilute sulphuric acid. The cathode in the cop voltameter gained 0·85 gm. in weight, while the volume hydrogen, reduced to N.T.P., was 300 c.c. Calculate the equi lent weight of copper, assuming that 1 litre of hydrogen at N.T weighs 0·09 gm.

15. A Daniell cell gives a current of 0·2 amp. for 45 m Calculate the change in weight of both electrodes. (E.C.E. copper = 0·00033 g. per coulomb. Equivalent weight of cop = 31·8; of zinc = 32·6.) *J.M.B.**

16. Describe a lead accumulator and explain how it wor If the polarities of the terminals of such a cell were not mark how would you discover which was the positive pole?

CHAPTER 35

VARIOUS CELLS

HE first step towards the production of a continuous electric ırrent was made partly as the result of a lucky accident. uigi Galvani (1737–98), an eminent Italian scientist, was miliar with electricity generated by friction or induction, ıd had found that when the electricity so generated was ıssed through a frog's leg, it caused it to twitch. The ıcky accident' consisted in the fact that he happened to ıve hung some frogs' legs on copper hooks near an iron ılcony, and he noticed that whenever one of them was own into contact with the iron, it twitched. His previous periments made it clear that the twitching ıs the result of an electric discharge, but thought (wrongly) that the electricity was ored up in the frog's leg (cf. storing electrophorus). His fellow-countryman ılta showed, however, that the essential ıture was the two different metals, copper d iron, the frog's leg merely acting as a conctor, and indicator. From this point he on evolved the simple voltaic cell of Fig. /1, in which, however, zinc takes the place iron. The liquid is dilute sulphuric acid.

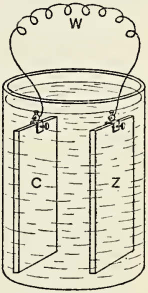


Fig. 35/1

Our studies in potential (Chapter 33) ggest that if a flow of electricity takes ıce from C to Z when the two plates are ınected, then C must be at a higher potential than Z. In s case ought we not to be able to show the difference of tential by means of a gold-leaf electroscope?

When we make the attempt, the gold leaves show no ceptible divergence, and at first we think that perhaps the ctricity is of a different *kind* from what we have met with electrostatics. However (though we will not enter into ıctical details), there are ways of 'magnifying' the potential ference, and we find then that a gold-leaf electroscope is

affected in the usual way. We are, in fact, dealing wit potential differences of the same kind as we met with in ou work on electrostatics, but of much less magnitude.

Theory of Action of Cell. To begin with, we will consider copper plate and a zinc plate dipping in dilute sulphuric aci with no connecting wire.

If pure zinc is used, a little goes into solution and a tin amount of hydrogen appears at the copper plate, but th action quickly stops. Let us see why.

When zinc dissolves it becomes zinc *ion* ($Zn \rightarrow Zn^{-2e} + 2e$ causing the solution near the plate to be positively charge (Zn^{-2e} means that each zinc atom, originally neutral, has los two negative units. The zinc ion is therefore positivel charged.) The plate itself is negatively charged due to th presence on it of free electrons (the '$+2e$' of our equation Soon it is unable to throw any further ions into solution, f being positively charged they are both held back by th negatively charged plate itself, and pushed back by th positively charged solution which surrounds it.

There are of course many hydrogen ions in the solution ($H_2SO_4 \rightarrow 2H^{-e} + SO_4^{2e}$). Some of these are driven (by the positively charged zinc–ion solution) towards the copper plate, to which they pass on their positive charges, becoming ordinary hydrogen ($2H^{-e} + 2e = H_2$). The action soon ceases, because the copper plate quickly acquires a sufficiently strong positive charge to repel any further hydrogen ions.

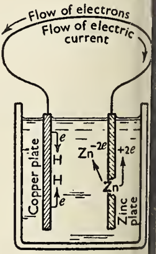


FIG. 35/2

At this stage the copper plate, owing to its positive charge, will have acquired a certain positive potential, while the zinc plate will have a certain negative potential. The diffe ence of potential between the two is known as the *E.M.I* (*electromotive force*) of the cell, because it is this differen which, if the plates were joined by a wire, would produce movement of electricity.

So far the plates have not been connected, and the cell said to be *on open circuit*. Now let a connecting wire l

ıtroduced. The electrons accumulated on the zinc plate ow to the copper, neutralising the positive charge there, and ıaking it possible for hydrogen ions to approach once more nd be discharged ($2H^{-e} + 2e = H_2$). The student can show ır himself that more zinc will now pass into solution. hus we have a continuous *current* of electrons—from the nc through the wire to the copper plate, where they add ıemselves to the hydrogen ions. In the solution itself, we ay regard the flow of positive charges (carried by the ydrogen ions, H^{-e}) from zinc to copper, as equivalent to a ɔw of negative charges, i.e. of electrons, from copper to nc. Thus the electron current (negative electricity) is mplete. The direction of the current of positive electricity of course in the opposite direction.

Note that for every two electrons passed on by the zinc ı *electrical* action), one atom of zinc goes into solution (a *emical* action). In other words, the quantity of electricity wing round the circuit is proportional to the amount of ıc which goes into solution (cf. Faraday's First Law of ectrolysis on p. 424). We may, in fact, say that the voltaic l is a contrivance for converting chemical energy into ctrical energy, the amount of the latter being proportional the amount of chemical action.

Defects of the Simple Voltaic Cell. We shall presently be dying the action of the *ammeter* and *voltmeter*. For the sent experiment it is sufficient to ɔw that the former is an instrunt for measuring the strength of electric current, and the latter for asuring differences of potential—ch smaller differences than we met h in our work in electrostatics.

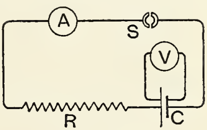


FIG. 35/3

 represents a simple voltaic cell,[1] preferably with an extra ding screw attached to the top of each plate. It is nected in series to a resistance R of about 40 ohms and ammeter A, which should read to about 50 milliamperes. switch S enables us to open or close the circuit at will.

[1] Notice the conventional representation—long stroke and short ke. The long stroke represents the positive plate, in this case the ɔer.

The voltmeter V, reading up to 2 volts, is connected acro the terminals of the cell. Do not put the copper and zi plates in the acid until all the connections have been made.

When all is ready, put the plates into the acid, but ke the switch open until the voltmeter has been read. This giv the E.M.F.—i.e. the potential difference with the cell ' open circuit.' Now close the switch, and read the ammet and voltmeter, repeating the readings every quarter minut They soon show a falling off, finally becoming steady at much lower value than originally. Now open the switc The reading of the voltmeter slowly rises, finally reachi a value not much less than at the beginning.

How are we to account for this falling off in the streng of the current and in the E.M.F.?

Most of the trouble is due to *polarisation*—i.e. the producti of bubbles of hydrogen on the copper plate. This formati of hydrogen is, of course, quite in accordance with theor and there would be no trouble if the hydrogen *left* the copp plate at the instant it was produced. Actually, there always a good quantity clinging to it. As a result, part the area of the plate is put out of action, being separat from the acid by the hydrogen. It is as though the pla were steadily reduced in size, until a point is reached at whi bubbles leave the plate at the same rate as they are produc We shall see later that a reduction in the size of the pl causes an increase in the *resistance* of the circuit, and corresponding reduction in strength of current.

Again, we have seen that when a voltaic cell is worki hydrions—(i.e. hydrogen ions) constantly reach the copp and (combining with the electrons that have come from t zinc via the wire) are turned into hydrogen. But owing the layer of hydrogen acting as a barrier, a great many these hydrions are unable to reach the plate. As a resu just outside the layer of hydrogen bubbles we have a lay of hydrions. These are, of course, positively charged, a they repel other hydrions which otherwise would have b able to move up to the plate. This reversal in the directi of movement of the hydrions corresponds to a tenden towards reversal in the direction of the current. It is n strong enough actually to reverse it, or even to bring it

ero, but it does greatly weaken it. We express the state of iings by saying that 'a back E.M.F. is set up.'

The first remedy that comes to one's mind is to remove ie copper plate from time to time and brush the bubbles way. This was actually done at one time, but *chemical* ethods of removing the hydrogen were soon devised. We rrange for an *oxidising agent* to be present. As a result, the ydrogen is made to combine with oxygen and is converted to water. We shall have a good example this almost immediately, when we come consider the Leclanché cell.

So much for troubles at the copper plate. ow let us consider the zinc one.

According to the theory discussed on p. 2, there should be no hydrogen at the zinc ate. Actually there is a great deal, and more impure the zinc, the greater the nount of hydrogen. How are we to account it?

Most specimens of zinc contain considerable antities of impurities—lead, iron and carn, for instance. In Fig. 35/4 suppose B a particle of pure zinc and A a neighbouring rticle of lead (both greatly magnified for sake of clearness). Here, on a minute le, we have the materials for a voltaic l—two different metals immersed in acid, nnected not actually by a wire, but by the metal of the plate elf. The result is that we have *local action*—i.e. an electric rrent is set up in the direction shown by the arrows, and lrogen appears at A. In practice we have, of course, a ltitude of these local currents. Obvious results are

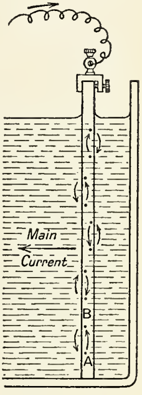


Fig. 35/4

(i) The effective area of the plate is reduced, because the acid cannot make contact with those parts which happen to be protected by a hydrogen bubble. Thus we have higher resistance and reduced strength of current.

(ii) The effective area is further reduced because certain portions of the zinc are concerned in local action instead of contributing to the main current.

ii) Much zinc is wasted—dissolved to no useful purpose.

The most serious point of all is that this wasteful local actio goes on when the cell is on open circuit—i.e. when the wi connection between the copper and zinc plates has bee removed. Theoretically, when the cell is on open circu the zinc should cease to be dissolved.

We could reduce the trouble by using much purer zi plates, but the best remedy is found to consist in *amalgamatio* Mercury is rubbed against the zinc plate by means of a pa of cotton wool previously dipped in dilute sulphuric aci The result is that the plate becomes covered with a thin fil of *amalgam* [1] of very uniform composition. Local acti takes place, of course, only when the surface of the plate of *variable* composition.

This discussion of the reasons why the current strength a simple cell soon declines, has of necessity been somewh lengthy. Let us sum up briefly.

Current strength falls off because of: 1. Polarisation, 2. Loc action.

1. Polarisation is caused by accumulation of hydrogen the copper plate. This

(i) reduces the effective area of the plate, so increasi the resistance and reducing the current;

(ii) makes it more difficult for hydrions to make conta with the plate, and so sets up a back E.M.F. T effective E.M.F., and therefore the current, a consequently reduced.

Remedy. Removal of the hydrogen as fast as it is forme usually by a process of oxidation.

2. Local action is caused by the fact that, owing to t presence of impurities, adjacent portions of the zinc pl differ in chemical composition and behave like separ plates. Thus numerous local currents are set up. The resu are as just set out (p. 445).

Remedy. Amalgamation.

The Daniell cell. In this cell, invented by J. F. Daniell 1836, the zinc is surrounded by dilute sulphuric acid as Volta's simple cell. The acid, however, is contained in a poro pot, and so does not touch the copper, which in this case

[1] An amalgam is an alloy one constituent of which is mercury.

ıe outer vessel itself. The space between the porous pot ıd the copper vessel is filled with a saturated solution of ›pper sulphate (Fig. 35/5).

The action which takes place is as follows:—

(i) Electrons are produced on the zinc plate and travel through the wire to the copper exactly as described in connection with the simple cell (p. 443).

(ii) Copper sulphate in solution is ionised thus:—

$$CuSO_4 = Cu^{-2e} + SO_4^{+2e}.$$

(iii) The electrons which have travelled to the copper plate convert copper *ion* into copper.

$$Cu^{-2e} + 2e. = Cu.$$

This copper is deposited on the inside of the copper vessel. (In the *simple* cell hydrogen bubbles would have been formed, producing polarisation.)

iv) As the copper container is kept negatively charged by the constant receipt of electrons, the positively charged hydrogen ions from the inner pot move towards it, and so enter the copper sulphate solution. Thus the latter is constantly gaining hydrogen ions at the same time that it is losing copper ions—i.e. it is being gradually converted into sulphuric acid.

'o keep the copper sulphate solution up to strength, stals of copper sulphate are often placed on a perforated lf just inside the copper container.

'he Daniell cell has the advantage of giving a very constant I.F. Its resistance, however, is rather high, and so it s not give a very strong current (in Chapter 37 we ll see that current strength varies *inversely* as resistance). ess it is going to be wanted again very soon, it must be hed out; otherwise the two liquids diffuse into one another ough the porous pot. Thus it needs a considerable amount ttention.

he Leclanché cell. In this cell we have zinc and *carbon* ead of zinc and copper, and the liquid used, instead of ıg dilute sulphuric acid, is a strong solution of ammonium ›ride. The carbon rod is contained in a porous pot, the e between rod and pot being closely packed with a mixture

of powdered charcoal and manganese dioxide. A section
the cell is shown in Fig. 35/6.

The action that takes place is often summed up brie
by saying that the ammonium chloride solution acts on t
zinc according to the equation

$$2NH_4Cl + Zn = ZnCl_2 + 2NH_3 + H_2.$$

The zinc chloride ($ZnCl_2$) and ammonia (NH_3) both
into solution. Hydrogen is deposited on the carbon pla
where the manganese dioxide causes it to be oxidised to wat

$$2MnO_2 + H_2 = Mn_2O_3 + H_2O.$$

A full explanation, however, would have to take accou
of the part played by the electrons, as in the case of t
Daniell cell just discussed.

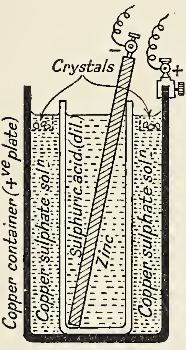


FIG. 35/5

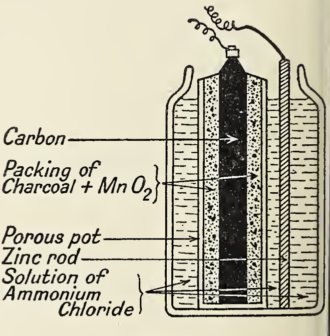


FIG. 35/6

Notice that the powdered charcoal surrounding the car
rod may be regarded as an extension of the latter, and m
of the hydrogen is produced among this powder. As t
latter is in intimate contact with manganese dioxide, oxidat
is greatly hastened. All the same, it is not fast enough to d
with the hydrogen at the same rate as it is produced, and s
the cell is in use for some time it becomes polarised. Gi
a period of rest, the manganese dioxide soon oxidises t
accumulated hydrogen, and the cell is then as good as e

'rom this it will be seen that the Leclanché cell is particularly uitable for *intermittent* work, such as for ringing an electric ell, or for telephone calls.

We may sum up its advantages thus:—

(*a*) It is cheap and easy to maintain, seldom requiring any attention except the addition of water to replace losses by evaporation. The ammonium chloride rarely needs renewal, and when it does, costs only a few coppers. The zinc need not be amalgamated, and when the cell is on open circuit is not attacked by the ammonium chloride solution. The zinc rod lasts for a very long time, often for years.

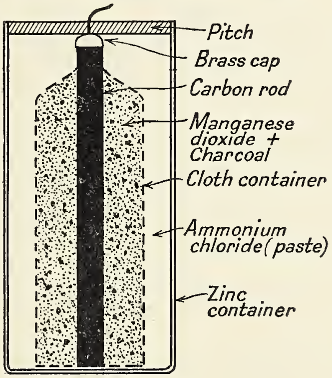


Fig. 35/7

(*b*) Ammonium chloride solution is not corrosive, so no great harm is done if the cell should be upset—an important point because it is often used in houses.

(*c*) Until polarisation sets in, it has a fairly high E.M.F. (about 1·5 volts).

:ts chief disadvantage—unsuitability for giving a steady 'rent for any length of time—has already been mentioned.

Dry Cell. The so-called 'dry cell' is really a modified :lanché. It is much used for cycle lamps and other electric

torches, and quite often for ringing a house bell (instead o the ordinary Leclanché). The high-tension battery of wireless set consists of a number of dry cells.

The best way to study the construction of a dry cell is t get hold of a 'spent' one and take it to pieces. As in th Leclanché cell proper, we find a carbon rod surrounded b manganese dioxide (mixed with powdered charcoal), bu these are enclosed in coarse cloth instead of in a porous po The zinc rod is represented by the zinc case itself, and instea of a *solution* of ammonium chloride, we have a *paste* made u of ammonium chloride, water, plaster-of-Paris and flour.

Questions

1. What is meant by the electromotive force of a cell, and wh is its origin? Explain why with some cells it falls below a norm value after the cell has been in use for some time. *O.C.*

2. Explain the action of the voltaic cell in terms of the ion theory.

3. A Daniell cell gives a current of 0·25 amp. for 2 hou How much zinc is dissolved? (The electro-chemical equivalent hydrogen is 0·00001044 gm. per coulomb; atomic wt. of zinc 65·4.) *Brist.**

4. A Daniell cell is giving a current of 0·3 amp. In what ti will 1 gm. of zinc have been dissolved? (Electro-chemi equivalent of zinc = 0·000341.)

5. Draw a sectional diagram of a Daniell cell and explain why the zinc rod should be amalgamated, (*b*) how polarisati is prevented. *Dur.*

6. Explain the terms *local action* and *polarisation*.
Describe experiments that you could perform to illustrate t action of a primary cell, using the following apparatus: rods copper or carbon, impure zinc and amalgamated zinc, a sup of insulated copper wire, dilute sulphuric acid, and a magne compass. *Camb.*

7. Describe a dry cell and give a short explanation of its mo of action.

CHAPTER 36

CURRENT MEASURED BY ITS MAGNETIC EFFECTS

OR many years men had suspected that there was some close ›nnection between magnetism and electricity. They had ›en struck by the fact that there were two kinds of electrifica- ›n, just as there were two kinds of magnetic pole; and in ›th cases they had discovered the rule that like kinds repel ıd unlike kinds attract.

It was not until 1819, however, that definite evidence was ›tained of the possibility of producing magnetic effects by ›ans of an electric current. In that year the Danish pro- ›sor Hans Christian Oersted was giving a lecture illustrated experiments with a group of voltaic cells, and it chanced at part of the connecting wire (cf. W on p. 441) was in a ıghly north–south direction. On the table there was a ıgnetic needle supported in the usual way, so as to swing a horizontal plane. It would, of course, be pointing ıgnetic north and south. Oersted happened to bring the ›dle near the connecting wire of his battery, and noticed ›h astonishment that it was suddenly deflected so as to int almost east and west. On reversing the current he ınd that the magnet was again violently deflected, but in › opposite direction.

A year later Ampère followed up Oersted's work, and ›de a number of further discoveries. One of them is now ›ays referred to as ***'Ampère's Rule,'*** and it may be stated ıs: *Imagine a man to be swimming with the current and king at the needle. The north pole of the latter will then be ›ected towards his left hand.* Some illustrations are given Fig. 36/1. Fig. 36/1*a* explains itself, and, in accordance h the rule, the north pole of the needle will be deflected wards from the paper. In (*b*) it is important to notice t, in order to look at the needle, the man must be swimming *his back.* Fig. (*c*) illustrates a case that very commonly ›es in practice—a coil of wire passing both over and under needle. We have here a combination of (*a*) and (*b*), in

each of which the north pole is deflected outwards from th paper.

Before passing on, let us notice that Ampère's rule gives a easy answer to a question which often arises—viz.: Suppose w have access to the wires connected with the terminals of a ba tery, but not to the battery itself. How can we tell which wi is connected to the positive terminal and which to the negativ

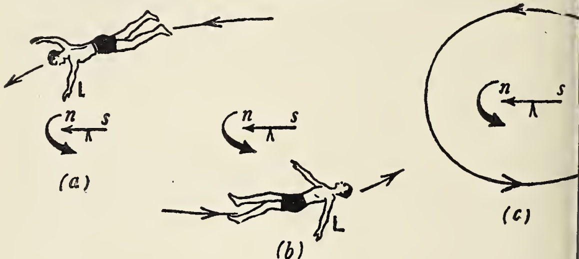


FIG. 36/1

We put a compass needle under the wire (Fig. *a*) and noti which way the north pole of the needle is deflected. Th gives us the position of the swimmer's left hand, and so obtain his direction. Obviously he is swimming *from* t positive terminal.

Lines of Force. Since a magnet is deflected when nea wire carring a current, there must be a *magnetic field* in t neighbourhood of the wire. With the help of Ampère's rule we can predict the direction of the lines of force ('the direction in which a free north pole would travel,' p. 372). Suppose the current is travelling in the direction

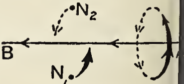


FIG. 36/2

AB (Fig. 36/2), and imagine a free north pole at N_1. This driven in the direction of the swimmer's left arm—i.e. o wards from the paper. A north pole at N_2 would be driv inwards, behind the paper. If you remember that our mu tried swimmer has always to face the free north pole, we that the latter would follow the circular path shown on right of the figure.

Maxwell thought of a rule which gives exactly the same sults as Ampère's, but which is much easier to apply in actice. Here it is—***Maxwell's Corkscrew Rule.*** *Suppose corkscrew is being screwed along the wire in the direction of current, then the direction in which the thumb rotates will e the positive direction of the lines of force.*

Apply this to Fig. 36/2, imagining that you are making the rkscrew advance in the direction AB. You can easily see at your thumb will follow the arrows (Fig. 36/3).

Now, all this is *prediction* from Ampère's rule. Is it ssible to show these lines of force by experiment?

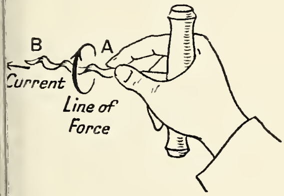


Fig. 36/3

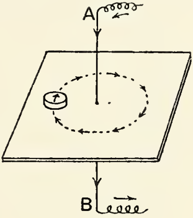


Fig. 36/4

Support a sheet of cardboard horizontally, and push a ce of rather stout copper wire, AB, vertically through it g. 36/4). Connect AB to the terminals of a battery, luding a resistance in circuit if necessary (you will need ne help from your teacher). It is also desirable that the uit should include a commutator switch so that the ection of the current can be readily reversed.

Vith the current passing in the direction AB, let a small ket compass rest on the card and mark the direction of needle with a pencil dot and an arrow (the latter indicating north pole). Move the compass needle into other positions the cardboard, repeating your pencil markings in each case. results will be found to confirm the Corkscrew Rule.

witch over the commutator so that the current now els in the direction BA, and put the compass successively r the old markings. The needle now points in the opposite ction.

Remove the compass and sprinkle iron filings on the card board. Tap gently. If the current is strong enough, th filings will arrange themselves in concentric circles (Fig. 36/5).

Coil of Wire. By means of a compass needle we can easil examine the lines of force produced by a *coil* of wire. W support a sheet of cardboard as before, and pass a coil copper wire through it as indicated in Fig. 36/6. The lin of force are in the direction given by the Corkscrew Rule.

It is important to notice the direction of the field at the centre of the coil. If only the part A of the coil were action, the direction of the field would be along CL—curvi off to the left of the perpendicular, CP. If only the part

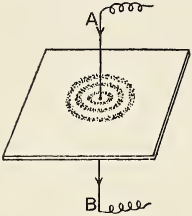


Fig. 36/5

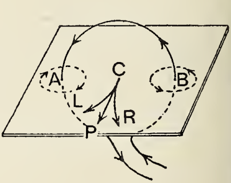


Fig. 36/6

were in action, its direction would be along CR—curving to the right. As both parts are acting, the direction is neit to the left nor right—i.e. it is at right angles to the diame AB. In a similar way, we can prove that it is at right ang to any other diameter. To satisfy this condition, *the directi of the field, at the centre of the circle, must be at right angles the plane of the coil*—an important result.

Notice next that the coil is behaving as a magnet wou if the latter consisted of a thin circular disc of steel (of t same cross-section and thickness as the coil). For if a f north pole were placed at C, it would be driven along C and that is exactly what would happen if our coil w replaced by the magnet just mentioned, provided its no pole were facing us. Such a magnet is known as a *magn shell.* In Fig. 36/6 the current is flowing in an anti-clockw direction, and we are then looking at the *north* pole of t corresponding magnetic shell. To sum up, *a coil of w*

onveying an electric current is equivalent to a magnetic shell, nd if we are so placed that the current is travelling anti-clockwise, en we are facing the north pole of the shell.

This, of course, gives us a 'rule' connecting polarity with rection of current, but it is much easier to remember it in e form suggested by Fig. 31/11 on p. 367.

The Solenoid. We have just been considering the case of a ngle coil carrying a current. Next ppose we make our wire into a lix, or close spiral, by winding it a umber of times round a cylinder ch as a cardboard postal tube. The re is supposed to be insulated. In g. 36/7, for simplicity, only four ils are shown.

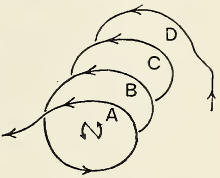


FIG. 36/7

Consider the coil A. It is equivalt to a magnetic shell, and with the rrent in the direction shown (anti-clockwise) the near face this would be a north pole. The remote face is a south le, and this would just 'cancel out' the near face of B nother north pole). Proceeding in this way, we see that the interior magnetic effects are cancelled out, and our ix behaves like a magnet of the same dimensions, with a rth pole at one end (in this case the near one) and a south e at the other.

A coil which, as a result of an electric current passing ough it, is equivalent to magnet, is known as a *enoid* (from a Greek word aning *pipe*).

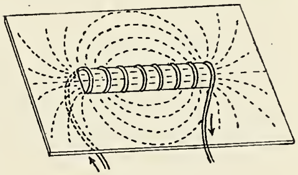


FIG. 36/8

From what has been said, should expect a solenoid be surrounded by the same t of magnetic field as a indrical bar magnet. We easily confirm this by experiment. In a piece of cardboard we cut a rectangular hole g. 36/8), of such size that our solenoid fits rather tightly it. We then scatter iron filings on the cardboard, and tapping they arrange themselves in characteristic fashion.

In this case, however, as our 'magnet' is hollow, we ca map the field inside. This internal field is found to be ver uniform, with its direction, as we should expect, parallel t the axis of the solenoid.

The fact that a solenoid is equivalent to a magnet can als be illustrated by the 'floating battery' experiment, devised by de la Rive about a century ago. The arrangement will be sufficiently clear from the figure. There, the current appears to an observer to be travelling anti-clockwise, so the near face should be a north pole. It will therefore be repelled by a magnet held in the position shown.

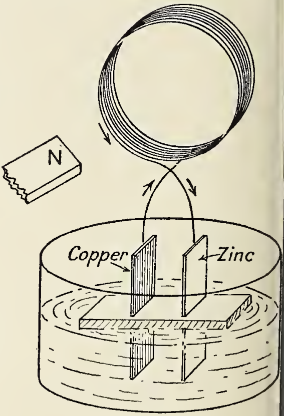


Fig. 36/9

Left to itself, the coil will turn until its *axis* is in the magnetic meridian—i.e. the plane of the coil will be at right angles to that meridian.

Definition of Unit Current. At first sight it might seem a very difficult thing to measure the strength of an electr current. But we know now that a current flowing in a c of wire produces a magnetic field at the centre of the co and the stronger the current, the stronger the field. No magnetic field is something that can be measured (p. 38 It should be possible, therefore, to measure the current th produces it. It is fairly obvious that the *strength* of t magnetic field at the centre of a coil must depend on

(i) the *strength* of the current;
(ii) the *radius* of the coil—the bigger the radius, the weaker will be the effect at the centre;

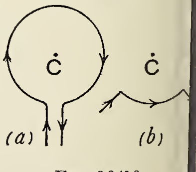


Fig. 36/10

(iii) the *length of arc* through which the current flows. Thus in Fig. 36/10*a* where the current makes a complete circle, the magnetic effect at C will be greater than in Fig. 36/10*b*, where the current passes through only a quarter of the circle.

These ideas lead us to a definition of the ***electromagnetic*** ***nit of current,*** which is *that current which, flowing through cm. length of an arc of radius* 1 *cm., produces a magnetic ld of unit intensity* (*i.e. of one oersted*) *at the centre.*

The unit just defined is too large for most practical purposes. he practical unit—the familiar *ampere*—is one-tenth of it.

As an exercise on the connection between current strength d magnetic field, let us work out the following:—

Example. *A current passes through three circular turns of sulated wire, side by side, of radius* 10 *cm. The field at the centre* 0·8 *oersteds. What is the strength of the current?*

Length of wire in each circle $= \frac{22}{7} \times 20$ cm., and in 3 circles

$$= 3 \times \tfrac{22}{7} \times 20 = 188{\cdot}6 \text{ cm.}$$

Suppose strength of current $= x$ e.m. units.

Now 1 e.m. unit flowing through 1 cm. of arc of radius 1 cm. oduces field of 1 oersted at centre.

$\therefore$ x e.m. units flowing through 188·6 cm. of arc of radius 1 cm. oduce field of $x \times 188{\cdot}6$ oersteds.

But radius is 10 cm.

$\therefore$ field will be $\dfrac{x \times 188{\cdot}6}{10^2}$ oersteds (inverse square law).

But field $= 0{\cdot}8$ oersteds

$$\therefore \quad \frac{x \times 188{\cdot}6}{10^2} = 0{\cdot}8$$

$$\therefore \quad x = 0{\cdot}424 \text{ e.m. units}$$

$$= \mathbf{4{\cdot}24\ amps.}$$

A Convenient Formula. From the definition given above we n easily derive a convenient formula.

Suppose a current of C amps. $\left(= \dfrac{C}{10} \text{ e.m. units}\right)$ flows ough n coils of radius r cm., and that the field at the centre the coil $=$ F oersteds.

The total length of coiled wire through which the current sses is $2\pi r \times n = 2\pi rn$ cm. Now, 1 e.m. unit passing

through 1 cm. of arc of radius 1 cm. produces a field of oersted at the centre.

$\therefore \quad \frac{C}{10}$ e.m. units passing through $2\pi rn$ cm. of arc of radi

1 cm. produce a field of $\frac{C}{10} \times 2\pi rn = \frac{\pi nrC}{5}$ oersteds at the centr

But the radius is r cm., so assuming the law of inverse squar the field will be $\frac{\pi nrC}{5} \times \frac{1}{r^2} = \frac{\pi nC}{5r}$ oersteds.

i.e. $$F = \frac{\pi nC}{5r}, \text{ or } C = \frac{5rF}{\pi n}.$$

If we had used this formula in the preceding exercise, should have had $F = 0{\cdot}8$, $n = 3$, $r = 10$, $C = ?$

$$\therefore \quad C = \frac{5 \times 10 \times 0{\cdot}8}{3\frac{1}{7} \times 3}$$

$= \mathbf{4{\cdot}24\ amps.}$ as before.

The Tangent Galvanometer. The tangent galvanometer a current-measuring instrument based on the principles have been discussing. It consists of a number of turns of insulated wire wound on a circular wooden frame. At the centre of the coil a *short* magnetic needle is suspended. In order that accurate readings may be taken, a long aluminium pointer is fixed at right angles to the needle. This pointer moves over a scale marked (usually) in degrees, and, to prevent errors due to parallax, a circular strip of mirror glass is placed on the inner side of the graduati marks. In taking a reading, the eye is so placed that t aluminium pointer just 'covers' its image (cf. magnetomet p. 387).

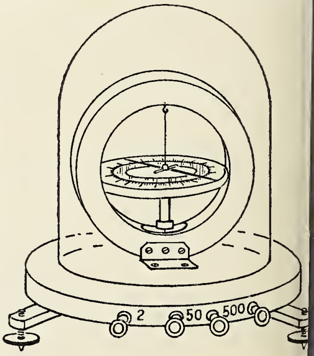


FIG. 36/11

The ends of the coil of wire are brought under the base of he instrument and soldered to the bases of two brass terninals. When we wish to measure a current, we join the nds of the wire carrying it to the brass terminals, thus includng the galvanometer coil in the circuit. In practice there re usually *four* terminals, the three spaces between them eing marked 2, 50 and 500. By selecting the proper pair terminals, we can make the current pass through either coils, or 50, or 500. If, for instance, we were dealing with rather strong current, we should join up to the terminals anding left and right of '2,' so as to send it through only vo coils.[1]

The instrument is levelled by adjusting three screws which pport the base, on the upper side of which a spirit-level is ted. Before passing the current, we must arrange that e plane of the coil shall be in the magnetic meridian. We this by gently turning the instrument until the zero of e scale is just under the end of the aluminium pointer. Vhen we are making this adjustment it is, of course, the *ile* that turns—the needle continues to point north and uth and the aluminium pointer east and west.)

Suppose we wish to compare the strengths of two currents iis is the purpose for which the tangent galvanometer is linarily used). Choosing a given pair of terminals—say ose left and right of the '50'—we pass each current in n through the instrument. In each case we read both ds of the needle, and take the average. Suppose the ter is 44° for the first current and 22° for the second. we shall show presently, the required ratio is *not*

$$= \frac{2}{1} \text{ but } \frac{\tan 44°}{\tan 22°} = \frac{0{\cdot}966}{0{\cdot}404} = \frac{2{\cdot}39}{1}.$$

f we possess certain information about the galvanometer, can find the actual strength of each current in amperes.

[1] It might be thought that by sending the current, say, through turns, the effect would be 250 times as great as when it is sent ough only 2. Actually, however, the *resistance* is very much ter in the former case, partly because of the greater length of wire, tly because of its smaller diameter. This higher resistance means ced current, and so there may be little or no advantage in using larger number of turns. There is a very marked advantage, ever, if the resistance of the galvanometer is small compared with total circuit resistance.

To get all this clear we must now consider the theory of th instrument.

Suppose NS represents the plane of the magnetic meridia in which, it will be remembered, the coil was set before th current was passed. On passing this current, a magneti field is set up which at O, the centre, is at right angles to th plane of the coil and is equal to $\frac{\pi n C}{5r}$, where n is the numbe of turns, C is the strength of the current in amperes, and is the radius of the coil (p. 458).

The needle is short, so we may take it that at P and Q th field also has this value approximately, and that the direction of the field is at right angles to NS.

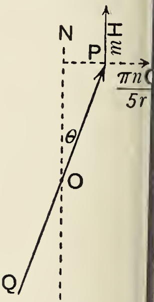


Fig. 36/12

Suppose the strength of the earth's field is H, the pole strength of the needle is m, and the angle through which the needle is deflected is θ.

The earth's attractive force on the pole of the needle is mH, and the *moment* of this force (p. 77) is $m\text{H} \times \text{NP}$.

The field produced by the current attracts the pole of the needle with a force of $m \times \frac{\pi n c}{5r}$, and the *moment* of this force is $\left(m \times \frac{\pi n c}{5r}\right) \times \text{ON}$.

As the needle is in equilibrium, the two moments we ha mentioned must be equal.

i.e. $$m\text{H} \times \text{NP} = \frac{m\pi n \text{C}}{5r} \times \text{ON}$$

$\therefore$ $$\text{C} = \frac{5r\text{H}}{\pi n} \times \frac{\text{NP}}{\text{ON}}$$

$$= \frac{5r\text{H}}{\pi n} \tan \theta.$$

Now r (radius of coil), H (horizontal component of eart

eld), π ($= 3\frac{1}{7}$) and n (number of turns) are all constants, so e may write

$$C = k \tan \theta$$

hen k is a constant equal to $\frac{5rH}{\pi n}$.

If we are comparing the strengths of two currents, C_1 and $_2$, then $C_1 = k \tan \theta_1$ and $C_2 = k \tan \theta_2$ (where θ_1 and θ_2 are ıe deflections which they respectively produce), so

$$\frac{C_1}{C_2} = \frac{\tan \theta_1}{\tan \theta_2}$$

. the strengths of the currents are proportional to the *ngents* of the angles of deflection, as already mentioned.

If we know the values of r, H, and n, we can find the actual rength of the current. Thus suppose r (mean radius of il) is 10 cm., $H = 0{\cdot}18$ oersted and $n = 50$, then

$$k = \frac{5rH}{\pi n} = \frac{5 \times 10 \times 0{\cdot}18}{3{\cdot}14 \times 50} = 0{\cdot}0573.$$

Thus a current which gave a deflection of 22° would have trength ($k \tan \theta$) of $0{\cdot}0573 \times \tan 22° = 0{\cdot}0573 \times 0{\cdot}404 =$)23 amps.

k is known as the *reduction factor* of the instrument. It ıy be found in the way already indicated, but it is difficult measure r with any great exactness. A better method is pass through the instrument a current of known strength ther measured by another instrument, or by the electrolytic thod described on p. 429), and observe the deflection. ppose, for instance, that a current of 56 milliamps ($= 0{\cdot}056$ p.) gave a deflection of 45°. Then

$$C = k \tan \theta.$$

$$\therefore \quad k = \frac{C}{\tan \theta} = \frac{0{\cdot}056}{\tan 45} = \frac{0{\cdot}056}{1} = 0{\cdot}056.$$

Ioving-coil Galvanometer. In the tangent galvanometer magnet (the needle) is small and light, while the coil is ıtively very large and heavy. Naturally, when a force is up between the two, it is the needle which moves, while coil remains stationary. If, however, we so arrange tters that the magnet is heavy, while the coil is relatively

light, any force set up between the two will cause the *coil* t move, while the magnet retains its position. An instrumen constructed on this principle is known as a *moving-coi galvanometer*.

The essential parts are shown in Fig. 36/13. The magne NS is cylindrical in form (this type shows little tendency t become demagnetised). Between its poles the coil is su pended by a thin wire of phosphor bronze, the latter bein connected at its upper end with a setting screw connected in turn with an arm which leads to the terminal T_1. The other end of the coil is connected, through a spring of phosphor bronze, with a terminal T_2. At the centre of the coil there is a core of soft iron, which serves to concentrate lines of force within the coil.

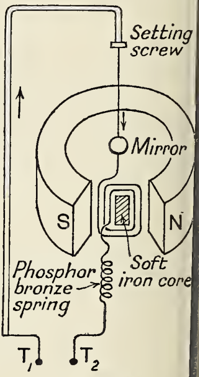


FIG. 36/13

Suppose a current enters at T_1, as shown by the arrows in the figure. This will traverse the coil in a counter-clockwise direction, and so the front face of the coil will become the equivalent of a magnetic north pole. This face will therefore move towards the south pole of the fixed magnet. As it does so, the upper wire twists, and a stage is reached at which the tendency of the coil turn towards the south pole is balanced by the torsion force set up in the wire. It can be shown that the ang through which the coil moves is proportional to the streng of the current.

We need some means of measuring this angle. An obvio method seems to be to solder a rather long, light pointer to the wire, so that as the latter turns the pointer can move over a suitably placed horizontal scale (Fig. 36/14). This is sometimes done. A better method, however, is to make use of a much longer pointer of *light*. A small mirror, plane slightly concave, is attached to the wire (M in Fig. 36/1

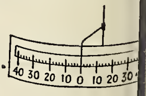


FIG. 36/14

ι lamp is placed about a metre away, and a narrow beam of ght from this falls on the mirror, and is reflected from it to semi-transparent scale. A very small movement of the ıirror causes a much larger movement of the spot of light n the scale.

By using a coil with a large number of turns in conjunction ith a strong magnet, together with a suspending wire as ıin as possible, galvanometers such as we are describing ın be made to be extremely sensitive. Indeed, it is often ecessary to employ a *shunt*—i.e. a conductor placed across ıe terminals T_1 and T_2 (Fig. 36/13), so that only a certain

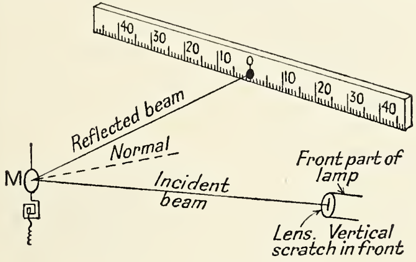


FIG. 36/15

own fraction of the current, perhaps one-thousandth, tually passes through the coils. There is usually a choice shunts, and this fraction can then be varied according to strength of the current. The way in which a shunt acts l be discussed more fully in the next chapter (p. 476).

Besides being much more sensitive than the tangent vanometer, the moving-coil instrument has another great vantage. Owing to the fact that the magnetic field in ich its coil rotates is so strong, other fields can be neglected comparison. Thus (unlike the tangent galvanometer) it ed not be set in any particular direction with regard to earth's field, and its readings are not affected by the sence of neighbouring pieces of iron, or of magnetic fields to the presence of magnets, electromotors, etc. It is (usually) 'dead-beat'—i.e. the coil comes to rest very ckly—and so a reading is soon taken.

On the other hand, the tangent galvanometer is cheape it needs no shunting, and it is not so easily damaged by th rather rough usage that a school instrument sometim receives. Further, one is saved the time and trouble require by the lamp-and-scale adjustments connected with the mirr galvanometer.

The Ammeter. One kind of ammeter (the word is a shortene form of ampere-meter) is a modification of the moving-coil galvanometer. The chief differences are that (i) the moving coil is pivoted on jewelled bearings instead of being suspended, and (ii) the movement of the coil is controlled by a spring, instead of by the torsion set up in the suspension wire.

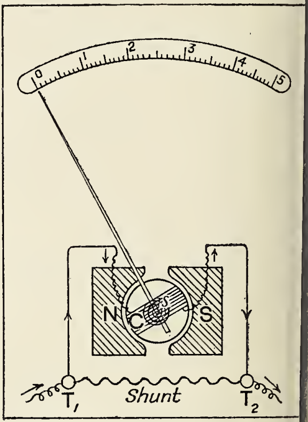


Fig. 36/16

Fig. 36/16 gives an idea of the general arrangement. The current enters at T_1, but most of it is shunted to T_2. A small fraction of it enters the instrument, and passes into the movable coil C, by means of a fine, flexible conductor. It passes out of it a similar way, and leaves the instrument at T_2. Inside t coil, but not touching it, is a core of soft iron to concentra the lines of force. *s* is the spiral spring resisting the mov ment of the coil, and connected with the coil is an ind finger moving over a graduated scale.

To *calibrate* the instrument—i.e. to secure that the readin shall be correct—it is placed in series with a standa instrument,[1] and the scale is so marked that the two instr ments give the same reading.

Ammeters are much used by practical electricians. Th

[1] The standard instrument is itself calibrated by the electroly process described on p. 429.

e not so sensitive as the galvanometers previously described, ıt they have the great advantage of being readily portable ıd of being very quickly read.

Questions

A

1. A current flows as shown in the diagram. Indicate the ·ection of the lines of force in the neighbourhood of AB, BC,) and DE.

2. AB and CD are two coils so suspended from ·eads as to be free to move towards or away m one another. Looked at from C, the current AB is flowing clockwise, and looked at from the current in CD is also flowing clockwise. licate the polarity of the two solenoids and ıce find whether they are attracting or repelling) another.

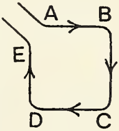


Fig. 36/17

3. State how the strength of the magnetic field at the centre a flat circular coil depends on (*a*) the number of turns, (*b*) the ius of the coil. *J.M.B.*

4. The coil of a tangent galvanometer contains 100 turns with nean radius of 10 cm. Where a certain current is passed ough it, a deflection of 45° is obtained. Find the strength he current. (H = 0·18 oersted.)

B

. Describe an experiment to demonstrate the nature of the gnetic field associated with a circular coil of wire carrying electric current. Give a diagram of the field and state a rule ting the direction of the current and the field.

xplain, by the aid of diagrams, the use of such a coil to ısure an electric current. *C.W.B.*

. Explain how you would show that a flat coil (such as of a tangent galvanometer) through which a current is ing, acts as if one face is a north pole and the other a south . *Camb.**

Give a labelled diagram of a galvanometer in common use explain the mode of action of the instrument. *Lond.**

In a certain tangent galvanometer a current of 2 amp. gives eflection of 45°. What current would be required to give a ection of 54°? What deflection would be produced by a ent of 1 amp.? (tan 54° = 1·38 and tan 26·6° = 0·500.)

5. If the coil of a tangent galvanometer has 4 turns of ra
8 cm., what is the current in amperes which will produc
deflection of 45°? ($H = 0{\cdot}18$ oersted.) *Lond.**

6. How would you find the reduction factor of a tang
galvanometer experimentally?

A tangent galvanometer has three sets of windings with 5,
and 50 turns respectively, all of the same radius. A curren
0·1 ampere gives a deflection of 45° with the 20-turn coil. W
will be the deflection observed when the same current pa
through (*a*) the 5-turn, (*b*) the 50-turn winding? *Oxf.*

7. What is meant by the *reduction factor* of a tangent galva
meter, and how would you find it experimentally?

Calculate the reduction factor of a galvanometer with 10 c
of radius 10 cm., if $H = 0{\cdot}18$ oersted.

8. Seven circular coils of insulated wire, side by side, hav
diameter of 20 cm. When a certain current is passed thro
them, a field of 0·5 oersted is produced at the centre. Find
strength of the current.

9. A tangent galvanometer used in London, where $H = 0$
gave a deflection of 45° when a certain current was passed thro
it. What deflection would it give for the same current in Sydı
Australia, where $H = 0{\cdot}25$? Your working must be cle
shown. ($\tan 36° = 0{\cdot}72$).

10. Three currents are passed in succession through the s
tangent galvanometer, and are found to give deflections of
45° and 60° respectively. The first current is known to hav
strength of 0·58 amp. Find the strengths of the second and th

11. Describe, with a diagram, a simple type of moving-
galvanometer.

Explain how this instrument measures currents.

On what factors does the sensitiveness of such a galvanom
depend? *Oxf.*

CHAPTER 37

OHM'S LAW AND ITS APPLICATIONS

OTH in electrostatics and in current electricity we have equently considered flow of electricity as being due to fference of potential, just as flow of water is due to difference level. In the present chapter we shall consider the subject greater detail, and more especially we shall see how the iantities concerned can be measured.

An obvious question to be answered if possible is this: *To iat extent* does flow of electricity vary with difference of tential? If, for instance, A and B (Fig. 37/1) are points on a

Fig. 37/1

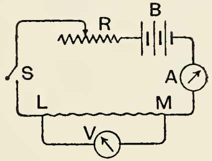


Fig. 37/2

iductor, and we have a current of 3 amps. when the potenl of A is higher than that of B by 1 volt, shall we obtain urrent of 6 amps. if we increase the P.D. to 2 volts?

Γo answer this question we set up apparatus as represented grammatically in Fig. 37/2. B is a battery consisting of ee 2-volt accumulators connected in series, and R is a riable resistance. LM consists of a good length, about ietres, of No. 22 manganin wire. The difference of potential ween its ends is measured by the voltmeter V, and the rent flowing through it by the ammeter A.[1] S is a tch by which we can readily open or close the circuit.

Starting with a fairly high resistance, we open the switch a few seconds and read A and V. We now reduce R and

[1] Strictly A records the total of the two currents that have passed ough LM and V, but as V has a very high resistance (p. 475, foote) the current passing through it is negligible.

read A and V once more. Proceeding in this way, we g results such as the following:—

Current . .	0·27	0·43	0·60	0·75	1·00	1·22
P.D. . .	1·11	1·76	2·48	3·05	4·13	5·00
$\frac{\text{Current}}{\text{P.D.}}$ . .	0·243	0·244	0·242	0·246	0·242	0·24

The results show that the current *is* proportional to t potential difference. They are summed up in the followi formal statement known as ***Ohm's Law*** (after the man w discovered the relationship). *If a conductor be maintai at constant temperature, the current passing through it will proportional to the potential difference between its ends.*

If the current (in amperes) is represented by C, and t P.D. (in volts) by E, we may write $\frac{E}{C} = R$ where R is a consta This constant ratio is known as the *resistance* of the conduct If $C = 1$ and $E = 1$, evidently $R = 1$, and so we get our u of resistance, known as the *ohm*—i.e. the ***ohm*** is *the sistance offered by a conductor through which a current of ampere flows when a P.D. of one volt is maintained betw its ends.*

So far we have considered the relation between P.D. a current only for a portion of the circuit. Is the relations true for the *whole* circuit, including the battery itself?

We can answer the question by the experiment illustra in Fig. 37/3. A number of Daniell cells—say five—are arranged in series. The circuit includes a switch S, an ammeter A, reading to say 1 amp., and a resistance of about 10 ohms.

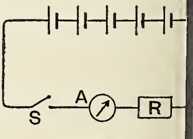


Fig. 37/3

If e is the E.M.F. of one cell—i.e. the P.D. between its plates when on open circuit—then with the arrangement of Fig. 37/3 the E.M.F. of the whole battery is We close the switch for a few seconds and note the curr recorded by the ammeter.

We now *reverse* one of the cells. The E.M.F. of the batt as a whole is now only $3e$. Once more we read the ammet

Finally, we reverse another cell, reducing the E.M.F. of the battery to e, and read the ammeter again.

We find that, corresponding to E.M.F.'s of $5e$, $3e$ and e, the respective currents are in the ratio 5 : 3 : 1—i.e. current is proportional to P.D. as before. Notice the points of likeness, and of difference, between this experiment and the preceding one. In both of them we obtain different values for the current corresponding to different values of the P.D. In both, we apply our varying P.D. to something of constant resistance—to a length of wire in the one case, to the complete circuit in the other. In both the P.D. is found to bear a constant ratio to the current which it maintains.

Going back to the statement of Ohm's Law given on p. 468, we see now that by 'conductor' we must understand not simply a wire, but any part of a circuit, including battery plates and solutions; and that because the law holds good for every part of a circuit, it is true for the circuit as a whole.

Before going farther, let us familiarise ourselves with Ohm's law by working out one or two very simple examples on it. Keep in mind that, mathematically, the law may be expressed by the equation $C = E/R$, where C is the current in amperes, E the P.D. in volts, and R the resistance in ohms.

Example 1. *A piece of wire was arranged similarly to* LM *in Fig.* 37/2. *When* V *recorded* 4·5 *volts, the ammeter reading was* 1·5. *What is the resistance of the wire?*

Here we have C = 1·5 amps. and E = 4·5 volts. Putting these values in the equation C = E/R, we have $1{\cdot}5 = \frac{4{\cdot}5}{\mathrm{R}}$

$$\therefore \quad \mathrm{R} = \mathbf{3\ ohms.}$$

Example 2. *In the experiment represented in Fig.* 37/3, *suppose each cell has an E.M.F. of* 1 *volt and a resistance of* 8 *ohms, and that the resistance* R *is* 10 *ohms, while that of* A *is negligible. What would be the reading of A* (a) *when the cells are arranged as in Fig.* 37/3, (b) *when one of them is reversed?*

(a) In the first case E = 5 × 1 = 5 volts.
Battery ('internal') resistance = 5 × 8 = 40 ohms.
External resistance = 10 ohms

∴ total resistance in circuit = 40 + 10 = 50 ohms

$$\therefore \qquad \mathrm{C} = \frac{\mathrm{E}}{\mathrm{R}} = \frac{5}{50} = \mathbf{0{\cdot}1\ amp.}$$

(*b*) In this case, $E = 3 \times 1 = 3$ volts.

Total resistance in circuit is 50 ohms as before

$$\therefore \qquad C = \frac{E}{R} = \frac{3}{50} = \mathbf{0{\cdot}06 \text{ amps.}}$$

Specific Resistance. On p. 468 we defined the *ohm*—th unit of resistance—as the resistance offered by a conducto through which a current of one ampere flows when a P.D of one volt is maintained between its ends.

It has been found by most careful experiment and calcula tion that this is the resistance that would be offered by column of mercury of certain dimensions, and the ohm i now often defined as *the resistance offered to the passage of steady current by a uniform column of pure mercury*, 106·3 *cm in length and* 1 *sq. mm. in cross-sectional area, at a temperatur of* 0° *C.* This is the Board of Trade definition.

This definition evidently implies that electrical resistanc depends on (i) the material, (ii) its length, (iii) its cross section and (iv) its temperature. Later in the present chapte we shall see how all these points can be proved experimentall For the present we will merely state, without proof, the fact relating to (ii) and (iii), viz.—

(ii) The resistance of a wire is *proportional to its length.* F instance, a piece of copper wire 100 cm. long woul have twice the resistance of a 50 cm. length of th same wire.

(iii) The resistance of a wire is *inversely proportional to th area of its cross-section.* Thus if we had two equa lengths of wire of the same material, the cross sectional area of the first being 1 sq. mm. and of th second 2 sq. mm. the resistance of the second wi would be half that of the first.

Now it is very often necessary to calculate the resistan of a certain length of wire of given diameter. We can do th provided we know what is called the ***specific resistance*** ***resistivity*** of the substance. This is defined as *the resistan of a conductor of that substance,* 1 *cm. in length and* 1 *sq. c in cross-section.*

N.B. It would be shorter, but entirely wrong, to define , as 'the resistance of a cubic centimetre of that substance.' ur 'cubic centimetre' might consist of 100 yards or so of very ne wire, and its resistance would be very high.

Example 3. *From the information given in the definition, p. 470, lculate the resistivity of mercury.*

Length 106·3 cm. and cross-section 1 sq. mm. gives resistance f 1 ohm.

$\therefore$ length 1 cm. and cross section 1 sq. cm. (= 100 sq. mm.) ves resistance of $\frac{1}{106{\cdot}3} \times \frac{1}{100}$

$$= 0{\cdot}0000941 \text{ ohms}$$

$$= 94{\cdot}1 \text{ microhms}$$

i.e. resistivity = **94·1 microhms.**

N.B. A microhm = one-millionth of an ohm. Resistivity is ten expressed in microhms.

The Cell as an Electricity Pump. Suppose H is a tank of ater at a higher level than another tank L. If the two are nnected by a pipe CDE, ater flows from the higher vel to the lower. In the me way, electricity passes om a point at high potential one at a lower potential, tential in electricity corre- onding to level in water.

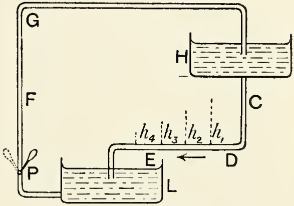


FIG. 37/4

We have had all this be- e, but let us now pursue e question a little farther.

Let us arrange a second pipe FG passing from the lower nk to the higher. Now that we have provided a complete th, is there any hope that the water will just go round d round continuously, from H to L via CDE, from L back H via FG and so on?

Not the slightest—that would be perpetual motion. If, wever, we provide a *pump* at P, the case is entirely altered. e pump acts as a source of energy, lifting the water from

the lower level to the higher, and with its help it would b
quite possible to secure a continuous flow.

We have now a very helpful illustration of an electr
circuit. The electricity conveyed is represented by the wat
and the conducting path along which it travels is, of cour
represented by the pipes. The water level has its maximu
at H and its minimum at L. Correspondingly in a circu
that includes a voltaic cell, we find the highest potential
the copper plate, and this falls as we pass along the wire t
the lowest value is reached at the zinc plate. In our wat
circuit, low-level water is converted into high-level water b
the mechanical energy supplied by the pump, which co
responds in the electrical circuit to the chemical ener
produced in the cell.

The resistance in the electric circuit is, of course, repr
sented by the resistance which the pipe offers to the free fl
of water. To make this obvious, let us suppose that t
pipe is partly choked by growths of moss, etc., on t
inside.

Such resistance will, of course, reduce the current, and t
more the resistance increases, the weaker becomes the curre
We are reminded very much of Ohm's Law, C = E/R—t
current varying inversely as the resistance.

Finally, let us consider just one portion of the pipe, s
DE. The water is travelling against considerable resistan
in the direction shown by the arrow. At h_1, h_2 . . . we ha
made pinholes on the upper side of the pipe.

Thin jets of water spurt out from the holes, and we not
a rapid falling off in the *height* of these jets, indicating a ra
falling off in pressure.

Example 4. *A cell of e.m.f.* 1·5 *volts and internal resista
3 ohms is joined to the end of a resistance of* 5 *ohms. What curr
passes through the resistance, and what is the potential differe
across its ends?* Lond.*

Suppose C and Z (Fig. 37/5) are the tops of the plates and C
is the resistance.[1] The total resistance = 3 + 5 = 8 ohms. N
the total fall of potential over the whole circuit is 1·5 volts a
the fall is proportional to the resistance encountered.

[1] In order to bring out clearly the various points concerned,
problem has been worked out in greater detail than would ordinarily
required.

∴ the fall in passing through the resistance CAZ is $\frac{5}{8}$ths of the total fall—i.e. $\frac{5}{8} \times 1{\cdot}5$ or $0{\cdot}9375$ volt (the remaining fall takes place in the cell itself and is $\frac{3}{8} \times 1{\cdot}5$ or $0{\cdot}5625$ volt. Thus fall in external circuit + fall in internal circuit = $0{\cdot}9375 + 0{\cdot}5625 = 1{\cdot}5$ volts as we should expect.)

Now consider the resistance CAZ. The 'potential difference across its ends' we have found to be $0{\cdot}9375$ volts. The current passing through it is given by Ohm's Law,

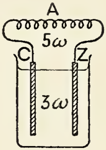


FIG. 37/5

$$C = \frac{E}{R} = \frac{0{\cdot}9375}{5} = \mathbf{0{\cdot}1875\ amp.}$$

We could have found the current more directly, because *for the whole circuit* $E = 1{\cdot}5$ volts and $R = 3 + 5 = 8$ ohms

$$\therefore \qquad C = \frac{E}{R} = \frac{1{\cdot}5}{8} = \mathbf{0{\cdot}1875\ amp.}\ \text{as before.}$$

Resistances in Series and in Parallel. The various resistances in a circuit may be arranged so that where one ends another begins. This is illustrated in Fig. 37/6. Starting from the positive pole of the battery we have—

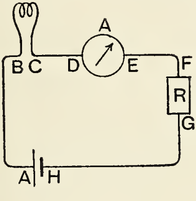


FIG. 37/6

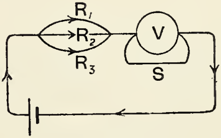


FIG. 37/7

(i) a wire AB, (ii) a lamp BC, (iii) a wire CD, (iv) an ammeter A, (v) a wire EF, (vi) a resistance box R, (vii) a wire GH, (viii) the battery itself.

In such a case the resistances are said to be ***in series.*** In practice it is seldom necessary to consider the very small resistance of the wires.

Two or more resistances, however, may be so arranged as to present *alternative routes* to the current. They are then said to be arranged ***in parallel.*** There are two examples illustrated in Fig. 37/7.

(i) the current divides itself between the alternativ routes R_1, R_2, R_3;

(ii) later it divides itself between the voltmeter V and th *shunt* (a sort of by-pass) S.

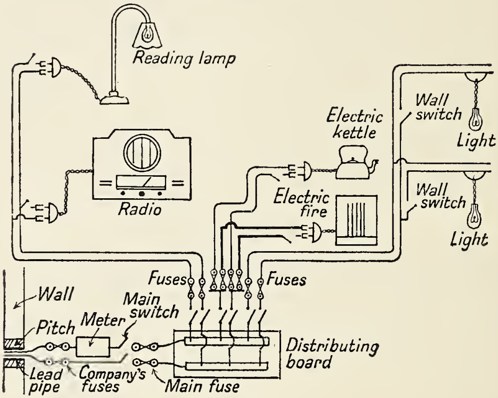


FIG. 37/8

A more elaborate example of resistances in parallel is see in the lighting circuit of a house. In Fig. 37/8, for instanc two resistances in parallel are represented by the two ligh on the right. (In practice there would probably be a numb of other lights on the same circuit.) On the left of the figur a reading lamp and wireless set are also seen to be connect in parallel.

When a number of resistances are in series, the *total* r sistance is obtained simply by adding the separate items together. When they are in parallel, however, the matter is not quite so simple.

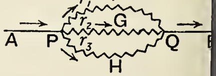


FIG. 37/9

Suppose a current C flowing along AP reaches (at P) three resistances PFQ, PGQ and PHQ of magnitudes r_1, r_2, r_3 arranged parallel. These reunite at Q, and the current then continu along the path QB (Fig. 37/9).

We wish to find the single resistance that would replace r_1, r_2 and r_3.

Suppose the fall of potential from P to Q is E, and suppose the currents that pass through the resistances r_1, r_2, r_3 are respectively c_1, c_2 and c_3.

Applying Ohm's law to the resistance PFQ we have

$$c_1 = \frac{E}{r_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(i)}$$

Similarly, considering the other two resistances we have

$$c_2 = \frac{E}{r_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(ii)}[1]$$

and

$$c_3 = \frac{E}{r_3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iii)}$$

Adding (i), (ii) and (iii), we have

$$c_1 + c_2 + c_3 = \frac{E}{r_1} + \frac{E}{r_2} + \frac{E}{r_3}.$$

But $\qquad c_1 + c_2 + c_3 = C$

and $C = \frac{E}{R}$ where R is the single resistance that would replace r_1, r_2, r_3.

$$\therefore \qquad \frac{E}{R} = \frac{E}{r_1} + \frac{E}{r_2} + \frac{E}{r_3},$$

and cancelling by E, we have

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}.$$

The result may obviously be generalised. If we have n resistances (r_1, r_2, r_3 . . . r_n) in parallel, then

$$\frac{1}{\boldsymbol{R}} = \frac{1}{\boldsymbol{r}_1} + \frac{1}{\boldsymbol{r}_2} + \frac{1}{\boldsymbol{r}_3} + \ . \ . \ . \ + \frac{1}{\boldsymbol{r}_n}.$$

[1] Notice the important special case when there are only *two* resistances r_1 and r_2 in parallel. $c_1 = \frac{E}{r_1}$ and $c_2 = \frac{E}{r_2}$.

$\frac{c_1}{c_2} = \frac{r_2}{r_1}$, i.e. the current is shared between the two branches in the *inverse* ratio of their resistances.

Example 5. *Two resistances of* 8 *ohms and* 12 *ohms respectivel are arranged* (a) *in series,* (b) *in parallel. Find* from firs principles *the resistance of each arrangement.* Lond.*

'From first principles' means that we must not use a formula The first arrangement (series) would obviously give a resistanc of $8 + 12 = 20$ ohms.

In the second case suppose the current C divides into two currents of c_1 (passing through the 8-ohm resistance) and c_2 (passing through the 12-ohm). Let E be the fall of potential between A and B (Fig. 37/10), and let R be the resistance of the combined arrangement.

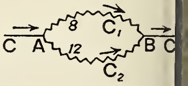


FIG. 37/10

Then $\quad C = \dfrac{E}{R}$ (i)

Also $\quad c_1 = \dfrac{E}{8}$ (ii) and $c_2 = \dfrac{E}{12}$ (iii)

But $\quad C = c_1 + c_2$

$$\therefore \quad \frac{E}{R} = \frac{E}{8} + \frac{E}{12}$$

$$\therefore \quad \frac{R}{1} = \frac{1}{8} + \frac{1}{12} = \frac{5}{24}$$

giving $\quad R =$ **4·8 ohms.**

N.B. Note that results such as we have just obtained ca easily be verified by experiment. We should simply pu the compound resistance (8 ohms and 12 ohms in paralle in the 'r_4' gap in the Wheatstone bridge (p. 481) and measu its resistance in the ordinary way. It should prove to b 4·8 ohms.

Action of a Shunt. Suppose we have a moving-coil galvan meter suitable for measuring currents from 0 to $\frac{1}{10}$ am We wish to convert the instrument into an ammeter capable of reading, say, from 0 to 5 amps. What can we do?

Diagrammatically, the galvanometer is represented in Fig. 37/11. The current enters at the terminal T_1 and leaves at T_2, and it must not exceed $\frac{1}{10}$ amp., or the spot of light would be turned beyond the limit of the scal

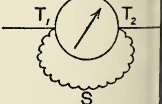


FIG. 37/11

We must so arrange matters that when the current in th

nain circuit is 5 amps., only $\frac{1}{10}$ amp. actually passes through he instrument.

To do this, we connect T_1 and T_2 by a piece of wire called *shunt*, through which most of the current passes. In this ase we wish to have only 0·1 amp. passing directly from T_1 to T_2, so 4·9 amps. must pass through the shunt. Suppose he resistance of the galvanometer is R_G ohms (we shall see little later, p. 482, how to find it). We wish to calculate hat of the shunt. Suppose the latter is R_S. Now the currents assing through the two branches are inversely proportional the resistances of these branches (footnote, p. 475).

$$\therefore \qquad \frac{0{\cdot}1}{4{\cdot}9} = \frac{R_S}{R_G}$$

$$\text{or} \qquad R_S = \frac{1}{49} R_G$$

hus the shunt must be of such dimensions that its resistance 1/49th that of the galvanometer.

N.B. A galvanometer or ammeter, since it has to be arranged series in a circuit, must have as low a resistance as possible. or $C = \frac{E}{R}$, and so if our galvanometer or ammeter causes R to greatly increased, it will cause C to be correspondingly reduced.

Let us next see how we could use our galvanometer as a *ltmeter*—i.e. as an instrument for recording the difference of potential between two ints A and B in a circuit (Fig. 37/12). Suppose we join A and B to the terinals T_1 and T_2 respectively, so that e instrument is in parallel with the main cuit. If C is the current that is shunted

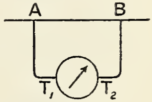


FIG. 37/12

rough the instrument, then $C = \frac{E}{R}$, whence $E = CR$. Our strument, being a galvanometer, actually records C (or can sily be made to do so). If, then, we find R once for all we ve the value of E (= CR).

But there is one fatal objection to all this. We have seen at the fall of potential between two points (such as A and B) a circuit is proportional to the resistance encountered.

Evidently if we link up our galvanometer in the way just described, we materially *alter* the net resistance between A and B, because, as we have seen, the resistance of two conductors in parallel is lower than that of either one of them.

If, however, the resistance of the galvanometer 'shunt circuit' is made *very high* compared with that of the direct line AB, the net resistance is not materially altered. E.g. suppose the original resistance between A and B is 4 ohms and that of the galvanometer is 996 ohms. The resistance r of the two conductors in parallel—what we have called the 'net resistance'—is then given by $\frac{1}{r} = \frac{1}{4} + \frac{1}{996} = \frac{1000}{4 \times 996}$

$\therefore \quad r = 3{\cdot}98$ ohms.

So to make our galvanometer into a voltmeter, we must first put a high resistance H in series with it (Fig. 37/13). This *modified* galvanometer is then joined in parallel to the two points whose P.D. we are finding. Because of the high resistance of the alternative path, very little current is diverted.

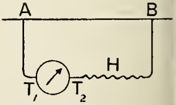


Fig. 37/13

Let us sum up.

1. To use a galvanometer as an ammeter we connect a known low resistance in parallel with the instrument so that only some known fraction of the current shall pass through it.
2. To use a galvanometer as a voltmeter we connect a high resistance in series with the instrument, so that the net resistance (and therefore the P.D.) between the two points whose P.D. is being found, shall not be materially affected.

Here are two examples.

Example 6. *A galvanometer is of* 5 *ohms resistance, and gives a full scale deflection when the current is* 15 *milliamps. Find the resistance needed to convert it into an ammeter reading to* 15 *amps. and give a diagram showing how this must be connected.* J.M.B.*

We must use a shunt of such resistance (r) (Fig. 37/14) that when a current of 15 amps. passes through the complete shunted instrument, only 15 milliamps. (= 15/1000 amps.) will pass through the

iginal coil, the difference $(15 - 0{\cdot}015)$ passing through the unt.

Now $\dfrac{\textit{current through shunt}}{\textit{current through coil}} = \dfrac{\textit{resistance of coil}}{\textit{resistance of shunt}}$ (footnote p. 475)

$$\therefore \qquad \frac{15 - 0{\cdot}015}{0{\cdot}015} = \frac{5}{r}$$

Working out, we get $r =$ ***0·0050 ohm.***

Example 7. *A galvanometer having a resistance of* 100 *ohms es a deflection of* 1 *scale division with a current of* 0·00001 *amp. w could you adapt the instrument for use as a voltmeter with cale division for* 0·01 *volt?* Camb.*

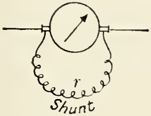


FIG. 37/14

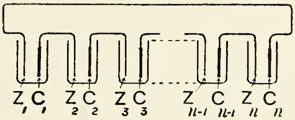


FIG. 37/15

'ig. 37/13 on p. 478, showing a high resistance H in series with galvanometer, will serve to illustrate the answer.

Vhen $E = 0{\cdot}01$, the current passing through the instrument th H in series) must be 0·00001 amp., as this will produce a ection of 1 scale division.

pplying Ohm's Law, $C = \dfrac{E}{R}$, we have $0{\cdot}00001 = \dfrac{0{\cdot}01}{R}$

$$\therefore \quad R = 1000 \text{ (ohms)}$$

'hus the modified instrument must offer a total resistance 000 ohms. As the galvanometer's own resistance is 100 ohms, 'ill be necessary to add a resistance of 900 ohms.

ells in Series and in Parallel. Cells are often grouped ether to form a *battery*, the object being to produce a nger current. There are two principal ways in which grouping may be carried out (i) in series, (ii) in parallel. netimes there is an advantage in combining the two hods.

/e have already referred once or twice to the 'series' ngement. Here the positive plate of the first cell is nected to the negative of the second, the positive of the nd to the negative of the third, and so on, as shown in 37/15 where Z_1, Z_2, etc., are the negative plates and C_1,

C_2, etc. the positive plates. Z_1 and C_n are then connected with the external circuit.

For simplicity let us suppose that the cells are simil and that each has an e.m.f. of E.

Let potential of $z_1 = p$

$\therefore$,, ,, $C_1 = p + E$
$\therefore$,, ,, $Z_2 = p + E$ (because it is connected with
$\therefore$,, ,, $C_2 = p + 2E$ (because higher than that z_2 by E)
$\therefore$,, ,, $Z_3 = p + 2E$ (because it is connected with
$\therefore$,, ,, $C_3 = p + 3E$, and so on.

Reasoning in this way, we see that the potential of c_n w be $p + nE$. Thus the E.M.F. of the complete battery w be the difference of potential between c_n and z_1 (the batte being on open circuit). This difference $= (p + nE) - p = n$ and we have the important result that *if a number of simil cells are connected in series, the E.M.F. of the battery is nE, where E is the E.M.F. of one cell and n is the number of cells.* (Whether the cells are similar or not, the E.M.F. of the battery equals the sum of the E.M.F. of the separate cells.)

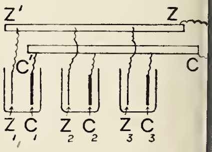


FIG. 37/16

Considering the cells as a number of resistances, the latter are, of course, in seri Thus the resistance of the battery is equal to the sum the resistances of the various cells.

Fig. 37/16 shows (diagrammatically) a few cells connect in parallel. The positive plates are joined up by wire form a single conductor CC′. Similarly, the negative pla are joined up to form ZZ′. The external circuit will th have its positive terminal at any point on CC′, and its negat terminal at any point on ZZ′.

Since the positive plates are all connected, they are all the same potential; there is no 'stepping up.' Similar the negative plates are all at the same potential. Thus t E.M.F. of the battery is the same as that of any one of t cells.

On the other hand, all the separate positive plates form, ractically, a single large positive plate, and similarly for he negative plates. The effect of this is to reduce the esistance.

As an example of the two methods of grouping, let us uppose we have four Daniell cells, each with an E.M.F. of volt and an internal resistance of 8 ohms. Grouped in eries, we should have a battery of E.M.F. = 4 volts, and nternal resistance 32 ohms. With parallel grouping, the .M.F. would be 1 volt and the internal resistance $8 \div 4 = 2$ hms. Which of the two arrangements is the better depends n the *external* resistance. Let us calculate the current roduced by each arrangement when the external resistance is) 4 ohms, (ii) 100 ohms.

(i) *External resistance small* (4 *ohms*).

Series grouping. E.M.F. = 4 volts. Total resistance $32 + 4$ ohms.

$\therefore C = E/R = 4/36 = 0{\cdot}11$ amp.

Parallel grouping. E.M.F. = 1 volt. Total resistance $2 + 4$ ohms.

$\therefore C = E/R = 1/6 = 0{\cdot}17$ amp.

(ii) *External resistance large* (100 *ohms*).

Series grouping. E.M.F. = 4 volts. Total resistance $32 + 100$ ohms.

$\therefore C = E/R = 4/132 = 0{\cdot}036$ amp.

Parallel grouping. E.M.F. = 1 volt. Total resistance $2 + 100$ ohms.

$\therefore C = E/R = 1/102 = 0{\cdot}001$ amp.

Generally speaking (as indicated by this example), when the ternal resistance is small compared with the internal, e parallel arrangement gives the stronger current; when it large, the series arrangement is better.

The Wheatstone Bridge. Suppose a current of c amps. (Fig. /17) flowing along AB, divides at B into the two branches FD and BGD, which reunite at D, c_1 being the portion of the rrent which flows along BFD and c_2 the portion flowing along GD. BFD is itself divided into two parts BF, FD, having sistances r_1, r_3 respectively. Now, as the potential is falling ntinuously along the path BFD and also along the path BGD,

there must be somewhere in BGD a point which has the sam potential as F. Let G be this point, and let the resistances o BG, GD be r_2, r_4 respectively.

By Ohm's law ($C = \frac{E}{R}$ or $E = CR$) the fall of potential fro B to F = $c_1 r_1$, and the fall from B to G = $c_2 r_2$.

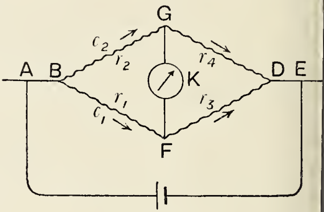


Fig. 37/17

But this fall is the same in both cases, for the potentials at F and G are equal.

$\therefore \quad c_1 r_1 = c_2 r_2 \quad$ (i)

Again, since potential at F = potential at G, the fall from F to D = fall from G to D.

i.e. $\quad c_1 r_3 = c_2 r_4 \quad$ (ii)

From (i) and (ii) we have

$$\frac{c_1 r_1}{c_1 r_3} = \frac{c_2 r_2}{c_2 r_4}$$

$$\therefore \quad \frac{r_1}{r_3} = \frac{r_2}{r_4} \text{ or } \frac{r_1}{r_2} = \frac{r_3}{r_4}.$$

If we know the value of r_3 and the *ratio* $\frac{r_1}{r_2}$, it is evide that we can easily calculate r_4. This is the principle of th *Wheatstone Bridge*, much used for the measurement of r sistance. We will now describe a common form of th instrument, making the letters correspond to the 'theoretica diagram of Fig. 37/17.

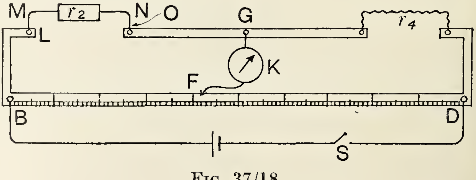


Fig. 37/18

The current enters at B, and part of it ('c_1') takes the pat BF, the other part going to G via the resistance r_2. Noti that between B and G, r_2 is the only resistance that *count*

L and OG are made of stout brass or copper bar, and M and
are short pieces of fairly thick copper wire—all of negligible
sistance. Similarly, r_4 is the only effective resistance
etween G and D.

BFD is a uniform straight wire stretched over a metre-
ale, and F represents a sliding contact which can be made
touch the wire at any desired point. F and G are connected
rough the sensitive galvanometer K.

In discussing the theory of the bridge, it was specified
at F and G must be at the same potential. We secure
is by moving the sliding contact along the wire until a
oint is reached at which no current flows through K. In
actice we begin by having a shunt attached to the galvano-
eter—otherwise we might get a rather damaging current
ssing through it. When we are in the neighbourhood of
e 'null point' or 'dead point,' we remove the shunt, and
can then detect even a very faint current. When we
ve obtained the null point we take the reading. If BF is,
y, 48·2, FD = 100 — 48·2. Since the wire is uniform,
sistance is proportional to length, so we have $\frac{r_1}{r_3} = \frac{48 \cdot 2}{51 \cdot 8}$.

The resistance r_2 is provided by a 'resistance box'—a piece
apparatus which can provide us with any required re-
tance as easily as a box of weights can supply us with any
sired weight. Suppose $r_2 = 3$ ohms.

Then
$$\frac{r_1}{r_3} = \frac{r_2}{r_4}$$

$$\therefore \quad \frac{48 \cdot 2}{51 \cdot 8} = \frac{3}{r_4}$$

$$\therefore \quad r_4 = \frac{3 \times 51 \cdot 8}{48 \cdot 2} = 3 \cdot 22 \text{ ohms.}$$

vo practical points may be noted.

. We choose r_2 so that F is not far from the middle of the
le. A slight error in reading does not affect the ratio
so seriously as it would if F were near one end.

. After obtaining a result (as above, where $r_4 = 3 \cdot 22$)
exchange r_2 and r_4, work out our answer afresh, and take
average of the two. This procedure corrects for 'end'

errors—i.e. errors arising from the fact that, owing to solde
ing difficulties, the ends of the wire are not *precisely* at 0·
and 100·0 on the scale. It also corrects for non-uniformit
of the wire. Thus our results would appear like this:—

Position	r_2	BF	FD	r_4 (calc.)	Mean
r_2 on left . .	3·00	48·2	51·8	3·22	} 3·23
r_2 on right . .	3·00	51·9	48·1	3·24	

Sometimes we are asked simply to find the *ratio* betwe
the resistances of two wires. In that case the wires are p
in the positions r_2 and r_4 (Fig. 37/18) and the required ratio
(*length FB*) $\div$ (*length FD*). We should get a second result b
interchanging them (see above), and taking the mean.

We could easily use a Wheatstone bridge to enable us
make a coil of given resistance. Suppose we wish to make
2-ohm coil from a quantity of insulated wire supplied-
German silver, perhaps.

First we find the resistance of a 1-metre length of the wi
Suppose this comes to 0·37 ohm. For 2 ohms it looks
though we should need $2 \div 0{\cdot}37 = 5{\cdot}405$ metres (540·5 cm
But any small error we made in finding the resistance
1 metre of the wire would be increased more than 5-fold
a length of 5·405 metres, so to get a better result, cut
exactly 6 metres and measure its resistance. Suppose th
comes to 2·23 ohms. By proportion, we find that the leng
for a resistance of 2 ohms would be $6 \times \frac{2}{2{\cdot}23} = 5{\cdot}381$ metr
(= 538·1 cm.), and we reduce our 6-metre length
to this amount.

Fig. 37/19

For convenience in use, the wire would now
be wound on a bobbin. Before winding, it
should be doubled, as shown in Fig. 37/19, so
that there shall be no magnetic effect when a
current passes through it (p. 493).

One or two other uses of the Wheatstone
bridge readily suggest themselves. One is that we could use

verify the laws mentioned on p. 470 relating to the resistance a wire. Suppose, for instance, we wish to show that the sistance of a wire is inversely proportional to the area of its oss-section. We take two wires of the same length and aterial, but of different diameters (measured by a microeter screw). Suppose they are d_1 and d_2. Then the first s a cross-sectional area of $\frac{1}{4}\pi d_1^2$, and the second of $\frac{1}{4}\pi d_2^2$, e ratio being $d_1^2 : d_2^2$. By means of the bridge, we now find e *ratio* of the resistances, which should be found to be $^2 : d_1^2$. Thus the law would be verified for this particular se.

Obviously, too, we could use the bridge to find the resistivity specific resistance) of a given substance. We find the retance of a piece of wire of that material, measure the length d diameter of the wire, and then work out the specific sistance as shown in Example 3 on p. 471.

Yet again, we could use it to show how the resistance of wire varies with temperature. The wire in question, in form of a rather long coil, is surrounded by a beaker of ter containing a thermometer. This coil serves as, say, in Fig. 37/18, r_4 being roughly equal to it in resistance e temperature of r_4 would remain constant, while that of ould be varied as desired by heating the beaker of water, temperature being observed on the thermometer. By ans of the bridge, we could find the ratio of the resistance r_2 to r_4 for various temperatures, and as the resistance $_4$ is constant, we have a measure of the change in that of r_2. may mention here that the increase of resistance *per ohm* raising the temperature from 0° C. to 1° C. is called the *perature coefficient of resistance* of the substance in question. he resistance of platinum has been observed over a wide ge of temperatures. Hence a coil of platinum, enclosed suitable container, can be used as a *resistance thermometer*. s used for finding a great variety of temperatures, those urnaces, flue gases, steam superheaters, etc.

omparison of E.M.F.s. We can find the E.M.F. of a cell means of a voltmeter. If, however, a voltmeter is not ilable, we can easily *compare* the E.M.F.s of various cells the following method, and if we know the actual value of of the E.M.F.s we can, of course, find that of the other.

The instrument we use is called a ***potentiometer***, and consis essentially of a straight uniform wire PQ of considerab resistance, stretched over a divided scale. Through the wi a steady current is flowing, say from a 4-volt accumulator I

Suppose PQ is 100 cm. long and has a resistance of 10 ohm If the other resistances in the circuit are negligible, we ma argue that over the whole length PQ the potential falls b 4 volts, and therefore the fall per centimetre is 0·04 volt (t fall in potential is proportional to the resistance, and in t case of a uniform wire, resistance is proportional to the length). Thus at N, 25 cm. from P, the potential is lower than that of P by $25 \times 0{\cdot}04 = 1$ volt.

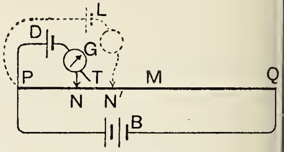


Fig. 37/20

Now suppose we connect D, the positive pole of a Daniell cell, to P. No current can flow round the Daniell circuit, for we have not yet completed th by connecting up T, the other terminal. The positive p will at once take up the potential of P.

If we take the E.M.F. of a Daniell cell to be 1 volt, t negative terminal will have a potential less by 1 volt th that of the positive terminal—i.e. 1 volt less than P. B the point N has such a potential. If, then, we make T tou the point N, there will be no current set up, because the t pieces of metal we are bringing into contact are already the same potential. In Fig. 37/20 a galvanometer is sho as included in the circuit, and this, of course, would unaffected.

We can sum up all this by saying that when no curre flows round the Daniell circuit, the E.M.F. of the cell is eq to the P.D. between P and N (the points at which it is c nected with the potentiometer wire). But, as we have se the P.D. between P and N is proportional to the *length* P Hence the E.M.F. of the cell is also proportional to th length.

It should now be easy to see how we make our comparis of E.M.F.s, say that of a Daniell cell with that of a Leclanc With the Daniell cell arranged as shown in the figure,

ove the sliding contact until the shunted galvanometer ves no deflection. We now increase the sensitiveness of the ılvanometer by removing the shunt, and make any slight ovement of the contact that may be necessary. Then we easure PN. Next we repeat the work with the Leclanché ll L (dotted lines in the figure) and measure PN′. Then we ıve $\dfrac{E.M.F.\ of\ Leclanch\acute{e}\ cell}{E.M.F.\ of\ Daniell\ cell} = \dfrac{PN'}{PN}$.

To secure the best results, it is a good plan to obtain a cond reading for the Daniell cell, and take the average of e two. This is to guard against the possibility that as the periment proceeds, there may be some slight change in the D. between P and Q.

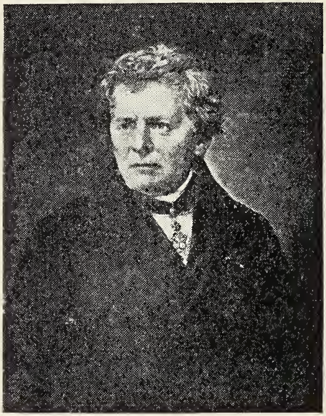
Our results might be set out thus.

Cell	Expt.	Length of PN or PN′ (cm.)	Mean value	$\dfrac{E.M.F.\ (Leclanch\acute{e})}{E.M.F.\ (Daniell)}$
›aniell	1st	26·2	26·25	1·42
,,	2nd	26·3		
eclanché	(one only)	37·5	37·5	

While the apparatus is still set up, it is worth while using to show that a Leclanché cell becomes polarised after being owed to give a current for a little while (p. 448). After ding that for the Leclanché, the null point was at 37·5 cm., could disconnect it from the potentiometer wire, and let give a continuous current for a minute (say through an ernal resistance of 4 or 5 ohms). We could then re-ınect, and find the position on the potentiometer wire ce more. The process would be repeated for longer and ger 'current' periods, the fall of E.M.F. being indicated a decreasing reading on the potentiometer wire.

ṙ. S. Ohm. In the course of the last two chapters we have l abundant reminders that electricity is a *quantitative* ence. Such things as the strength of a current, the re-ance of a circuit and the electromotive force of a battery matters of exact measurement, and Ohm's law is intimately cerned in them all. The question 'Who was Ohm?' is a y natural one.

Georg Simon Ohm was born at Erlangen in Germany i 1789. His father, a humble locksmith, had a deep respec for learning, and made great efforts to enable Simon to hav a much better education than he had had himself. He eve managed to keep his son at Erlangen University for an al too-short course of three terms. Simon then obtained wor as a private tutor in Switzerland and saved enough mon to finish his university course and pass his examinations.



G. S. OHM

By courtesy of the Director of the Science Museum, South Kensington

He had the great ambition of some day becoming University professor. For the time being he had to be cont with teaching in a very ordinary school—and a very go teacher he was. Unfortunately Germany was at this ti in great poverty as a result of the Napoleonic wars. Oh school was closed down, and he could not obtain anotl post. He went home, and busied himself in helping his fath now an ageing man, in the making and mending of loc Later, the skill he acquired in this way stood him in g stead in his practical scientific work, for he was able make much of his own apparatus.

A mathematical essay, 'written in a room without a fire,' ıttracted much attention, and he was offered and accepted ı post as teacher of mathematics and physics at the Jesuit High School in Cologne. In his scanty spare time he carried out researches in physics, and in 1826 was able to announce ıis famous law.

Strange to say, it aroused much opposition among certain nfluential people, and the Minister of Education went so far s to state publicly that 'a physicist who professed such ıeresies was unworthy to teach science.'

Ohm must have felt that his dreams of a university pro-essorship were ended now. He resigned his post, and for the ext six years earned a living as well as he could, largely y taking private pupils.

Meanwhile the importance of his law was beginning to be ecognised, to some extent in Germany, but to a far greater xtent abroad. Sir Charles Wheatstone, for instance (a ımous English physicist after whom the famous 'bridge' is amed), had the highest opinion of his work. In 1833 he eceived an appointment at the Nuremburg Polytechnic hool, and in 1841 the Royal Society awarded him the famous opley medal in recognition of his great services to science. ı 1849 came perhaps the greatest moment of his life, when, ter all his struggles against poverty and undeserved censure, was appointed a professor of the University of Munich, here he died a few years later.

Questions

1. The terminals of a cell, of E.M.F. 1·07 volts and internal sistance 0·5 ohm, are joined by 1 m. of wire of resistance 0·0025 m per cm. Calculate the current. What would the latter come if the length of wire were increased to 2 m.?

2. A filament lamp of resistance 4 ohms is run on a battery of M.F. 6 volts and an internal resistance 2 ohms. Assuming ere are no other resistances in the circuit, find (*a*) the current ength, (*b*) the potential drop across the filament of the lamp. *O.C.*

3. Define *ampere*, *volt* and *ohm*.

What length of wire of diameter 2 mm. and resistivity (specific istance) 0·000049 ohm-cm. is necessary to make a resistance 5 ohms? Describe briefly how the value can be roughly ecked by experiment. *Lond.*

4. State *Ohm's law*, and define *specific resistance* (*resistivity*). Describe how you would measure accurately an unknown resistance of about 1 ohm.

The resistance of 100 metres of copper wire of 0·50 mm diameter is 8·2 ohms. Calculate the specific resistance of copper *Camb.*

5. Find the resistance of 2 metres of eureka wire, the specifi resistance of eureka being 0·000044 ohm-cm., and the diamete of the wire 0·122 cm. How would you measure the resistanc of this wire experimentally? *C.W.B.**

6. When a galvanometer is connected (*a*) in series, (*b*) i parallel, with a resistance of 3 ohms, and the combination i joined to a battery of constant E.M.F. and negligible resistance the currents indicated are in the ratio of 3 to 4. Calculate th resistance of the galvanometer. *O.C.**

7. A current of 2 amp. passes through a resistance consistin of two coils of resistance 4 ohms and 6 ohms respectively, arrange in parallel. Calculate (*a*) the equivalent resistance of the coil (*b*) the current in each coil. *Lond.**

8. A battery of twelve accumulators is to be charged from 23 volt D.C. mains. If the E.M.F. of each cell during charging i 2·5 volt and the internal resistance negligible, what resistanc must be included in the circuit to give a charging rate of 8 amps. If a number of resistances of 100 ohm are available, how man would you use, and how would you arrange them so as to giv this charging rate? Draw a circuit diagram. Give reasons wh this method of charging is wasteful. *Camb.*

9. Describe in detail how you would measure an electr current by means of the tangent galvanometer.

A tangent galvanometer of resistance 1 ohm is connected i series with a resistance of 10 ohms and a battery, and a deflectio of 60° is obtained. When the external resistance is increased t 38 ohms the deflection is halved. What is the internal resistanc of the battery? *Camb.*

10. A cell is connected in series with a resistance of 1000 ohm and a tangent galvanometer of resistance 1000 ohms. Th deflection is 45°. If a resistance of 1000 ohms be placed i parallel with the galvanometer what will the galvanomet deflection be? *Dur.**

11. State *Ohm's law.*

Nine cells in series, of total resistance 3 ohms, are connecte to two points A and B, between which are resistances of 10 an 15 ohms in parallel. An ammeter shows the total current be 2 amp. What is (*a*) the E.M.F. of each cell, (*b*) the potenti difference between the points A and B, (*c*) the current in ea resistance between A and B?

12. What is meant by *resistivity* or *specific resistance*, and how vould you measure it in the case of nichrome, given a coil of wire ›f that material and any required apparatus?

A tungsten filament lamp dissipates 40 watts when used on ;40 volt D.C. mains. What is the resistance of the lamp when n use?

Find also the length of the filament if its diameter is 0·025 mm. nd the resistivity of the hot filament is 45×10^{-6} ohm cm. *Dur.*

13. State Ohm's law and define *electrical resistance.*

The terminals of a cell of E.M.F. 1·5 volts and internal resistance ohm are connected in series with two resistances A and B. A ; a 2-ohm coil and B consists of two resistances of 2 ohms and ohm arranged in parallel. Draw a diagram of the circuit. alculate (*a*) the total resistance of the circuit, (*b*) the current owing through the cell, (*c*) the currents flowing through the ›parate branches of B. *Camb.*

14. A battery of E.M.F. 12 volts and internal resistance 2 ohms connected in series with a 5 ohm resistance and a combination ›sistance composed of a 1 ohm coil and a 4 ohm coil in parallel. alculate the currents flowing through the 1 ohm and 4 ohm ›ils, and the voltage between the common terminals. *Dur.**

15. Two similar cells, each of E.M.F. 2 volts, are connected in ries to form a battery which sends a current through an external rcuit of resistance 6 ohms. The cells are then arranged in ırallel, and when this battery is used the current through the me external circuit is 14/25 of that previously. Calculate the ternal resistance of each cell. *O.C.**

16. State Ohm's Law, and describe an experiment to verify

Three wires, A, B and C, each have a resistance of 12 ohms. nd the values of the resistances made by (*a*) connecting all ree in series, (*b*) connecting all three in parallel, (*c*) joining A d B in series and connecting this composite resistance in rallel with C. *Oxf.*

17. State *Ohm's law.*

Why is the potential difference between the terminals of a cell t always the same as the electromotive force of the cell?

Resistances of 2 and 3 ohms, joined in parallel, are connected the terminals of a cell of E.M.F. 1·5 volt and internal resistance ohm. Calculate (*a*) the current through the cell, (*b*) the ference of potential between the terminals of the cell, (*c*) the rrent in the 2 ohms coil. *Camb.*

18. A galvanometer of resistance 63 ohms is connected in cuit with a battery, the E.M.F. of which is 10 volts. The istance of the battery and wires is 2 ohms. The galvanometer shunted so that one-tenth of the total current passes through Calculate (*a*) the resistance of the shunt, (*b*) the current ough the battery. *O.C.**

19. A battery of internal resistance 1 ohm is connected in serie with a resistance box, and galvanometer of resistance 50 ohms The latter is shunted by a wire of resistance X ohms. Whe the resistance of the box is 10 ohms, the current recorded by th galvanometer is half that shown when the resistance of the bo is 3 ohms. Calculate X. *O.C.**

20. A galvanometer having a resistance of 99 ohms is suitabl for measuring currents from 0 to 1/10 amp. Find the resistanc of the shunt that will make the instrument suitable for measurin currents from 0 to 1 amp. *O.C.**

21. Describe an instrument for the measurement of electri current.

A galvanometer of resistance 2 ohms is graduated to read u to 0·1 amp. Explain how you would modify it into a voltmete to read up to 10 volts. *O.C.*

22. Describe a moving-coil galvanometer, and in your diagra show the position of the coil when no current is passing.

If you were given a 2000-ohm coil and a moving-coil galvano meter, how would you compare the E.M.F. of a Daniell cell wit that of a Leclanché cell? What purpose is served by the co of high resistance?

23. Draw diagrams to show how three similar cells, each 1·4 volts e.m.f. and 5 ohms internal resistance, should be co nected to give (*a*) the highest possible e.m.f., (*b*) the lowe possible internal resistance. State both the e.m.f. and th resistance of the arrangement in each case. *J.M.B.**

24. Six cells, each of internal resistance 0·5 ohm and 1·1 vo E.M.F., are connected (*a*) all in series, (*b*) all in parallel, (*c*) i two parallel sets of three cells each. Calculate the current se in each case through a wire resistance of 1·2 ohm. *Dur.*

25. State *Ohm's law*, and describe how you would verify experimentally.

Two cells, each of E.M.F. 1·5 volts and internal resistan 2 ohms, are connected in parallel so as to supply current to a wi of resistance 4 ohms. Find the value of the current and t potential difference between the ends of the wire. *Oxf.*

26. Describe an instrument which can be used for measuri current by means of its magnetic effect.

Two accumulators, each of E.M.F. 2 volts and the same intern resistance, are connected in parallel and used to send a curre through a resistance of 7·5 ohms and an ammeter of resistan 2 ohms connected in series. The current found is 0·2 am Calculate the resistance of each cell. *O.C.*

27. Describe a method of comparing the resistances of two wires, giving a diagram of the circuit used.

Two wires, one of copper and one of iron, each 100 cm. long and 0·070 sq. mm. in cross-section, are connected in series, and a potential difference of 2 volts is applied to the arrangement. Calculate (*a*) the resistance of each wire, (*b*) the fall of potential along the copper wire.

(Specific resistance of copper $= 1{\cdot}77 \times 10^{-6}$, and of iron $= 10{\cdot}5 \times 10^{-6}$ ohms per cm. cube.) *J.M.B.*

28. Describe how you would make a 3-ohm coil if you were provided with a standard 1-ohm resistance, a reel of insulated resistance wire and any other apparatus which you might require.

If the length of the wire used in making the coil was found to be 1 metre and its diameter was 0·3 mm., what length of the same kind of wire, but of diameter 0·4 mm., would you cut off to make a 3-ohm coil? *Dur.*

29. Explain how you would compare the E.M.F. of two cells by means of a potentiometer.

A cell is connected across a resistance of 1 ohm, and the potential difference across the resistance is found to be 1·0 volt. When the resistance is replaced by one of 7 ohms, the potential difference is 1·4 volts. Calculate the E.M.F. and internal resistance of the cell. *Camb.*

30. What do you understand by (*a*) *electromotive force* of a cell, (*b*) *potential difference* between two points?

You are provided with the usual potentiometer equipment, an accumulator, and a standard cell of given E.M.F. How would you use them to determine the E.M.F. of a Daniell cell?

If a known low resistance is connected in parallel with the Daniell cell, what effect will it have on the potentiometer readings? What can you deduce from this observation? *Camb.*

31. Describe how you would compare the e.m.f.s of a flashlamp battery (about 3 volts) and a Leclanché cell (about $1\frac{1}{2}$ volts) by means of a potentiometer. Give the theory of the method employed, and point out any details of experimental procedure which ensure accuracy. *J.M.B.*

CHAPTER 38

ELECTROMAGNETIC INDUCTION

UNTIL 1831 some form of voltaic cell was the only known means of obtaining an electric current. No doubt certain practical applications would have been possible, but they would have been comparatively few, and only on a small scale. On a basis of zinc, copper and sulphuric acid we could never have had supplies of electrical energy sufficient to drive our trains and tram-cars, to light our towns and heat our houses on the scale that we see round us to-day—the cost would have been far too great.

What made the new developments possible was Faraday's

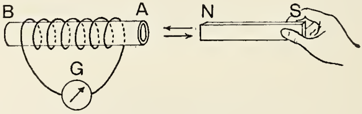


FIG. 38/1

discovery of how to convert mechanical energy into electricity and it is this conversion which we must now discuss.

We considered some of his experiments in our earlier book. In one of them (Fig. 38/1) he had a coil of wire, the two ends of which were connected with a galvanometer G. When a magnet NS was *held* in or near the coil, nothing happened. When, however, it was *suddenly moved* towards the coil, or into it, the galvanometer showed that a current was produced and when the magnet was quickly withdrawn, a current was again produced, but in the opposite direction. The current is said to be *induced* in the coil, and the phenomenon is known as *electro-magnetic induction.*

Carrying out the experiment to-day, we should make, say 250 turns of insulated copper wire round a cardboard tube about 4 in. long and an inch in diameter, and use a sensitive galvanometer. We could then easily show—

(i) that the strength of the induced e.m.f. depends on the speed of movement.

(What we should observe—with the help of the galvano-aeter—is that the strength of the induced *current* depends on he speed of movement. But since $C = E/R$, and R is onstant for the same coil, a greater or less value of C indicates greater or less value of E—i.e. of the induced e.m.f. It is etter to speak of the induced e.m.f. rather than of the induced urrent, because the strength of the latter depends not only n the movement of which we are speaking, but on the esistance of the circuit. Besides, an e.m.f. is induced even the coil is open, while a current flows only if it is closed.)

(ii) that by using a stronger magnet, we obtain a stronger induced e.m.f.—once again, indicated by a stronger current (the easiest way to obtain a stronger magnet is to tie another magnet to the original one, with like poles together);

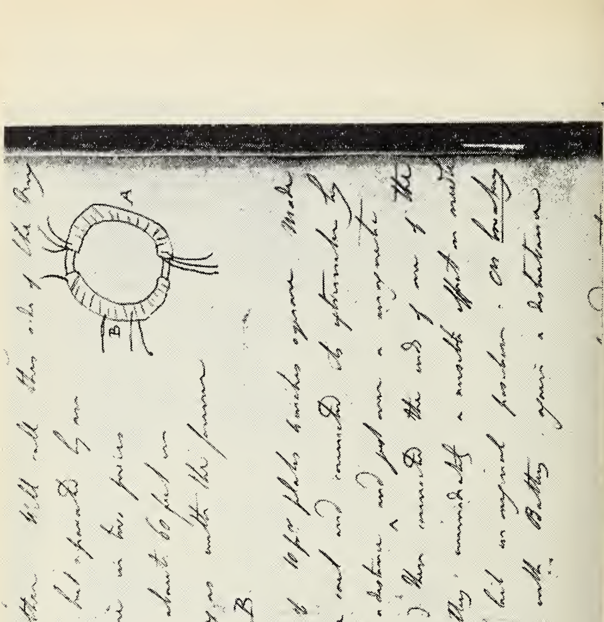
(iii) that (as we should expect) it makes no difference whether the magnet is pushed into the coil, or the coil is pushed over the magnet.

(iv) that the induced current is in opposite directions according as the magnet is being pushed into the coil, or withdrawn from it.

We must now look more closely into this question of the *rection* of the induced current. Let us first see whether e can predict it.

An electric current represents so much energy, and therefore ıen we produced one by moving a magnet, we must have ne work—we must have met with *resistance*—when we oved NS towards the coil and also when we pulled it away ig. 38/1).

If we met with resistance as we moved NS towards the il, the end A must have been acting as a north pole ('like les repel'), and therefore, looked at from N, the current ıst have been anti-clockwise (Fig. 31/11, p. 367). But must also have met with resistance in *withdrawing* the ıgnet. In that case the end A must have been attracting and so must have acted as a south pole. The current oked at from N) must therefore have been clockwise.



By courtesy of the Royal Institution

Our galvanometer indicates the direction of the current passing through it (needle moving to the right means that the current is entering at the ' + ' terminal). Thus we can put our conclusions to the test of experiment, and we find they are confirmed. They are summed up in what is known as ***Lenz's law***, which says that *If a conductor is moved in relation to a magnetic field, the direction of the current induced in it will be such as to oppose the motion.*

A striking experiment to illustrate Lenz's law is carried out by placing a heavy copper ring on the pole of an electromagnet (Fig. 38/2). When the current is switched on, the ring is thrown violently upwards. The switching on is equivalent to bringing a magnet near the coil, and a current is induced in the copper ring in a direction tending to push the magnet away. As the magnet is a fixture, the copper ring is pushed away instead.

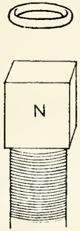


Fig. 38/2

Induced Current and Lines of Force. When we look at a magnet most of us see—just a magnet. But Faraday saw a great deal more. He saw the lines of force all round it; and he came to the conclusion that the e.m.f. giving rise to the induced current depended on the *rate* at which these lines of force were being cut by the coil. This would account for the fact that the more rapidly the magnet (or the coil) was moved, the stronger was the current. It would also account for the fact that the strength of the induced current depended on the strength of the magnet, because a stronger magnet would produce a greater concentration of lines of force than a weak one. All this would be true even if our coil consisted only of a single turn, and since the effect is experienced by each turn, the total effect will obviously depend on the number of turns.

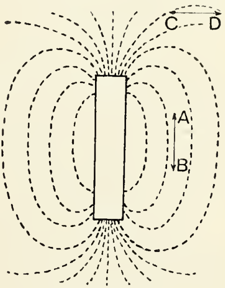


Fig. 38/3

It is quite possible to move the

coil so that it travels *in the direction of* the lines of forc instead of cutting *across* them—following a path such as A or CD in Fig. 38/3. In that case we obtain no induce current.

Coil instead of magnet. On p. 455 we saw that a coil i which a current is flowing—a *solenoid*—is equivalent to magnet. We should therefore expect that if the magne NS of Fig. 38/1 were replaced by a solenoid (CD in Fig. 38/ we should still have currents induced in AB; and this is found to be the case. Looked at from the left, the current in the solenoid would have to be anti-

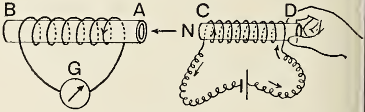


Fig. 38/4

clockwise for the end C to be equivalent to a north pol Lenz's law tells us that as CD is pushed near to AB, th equivalent of a north pole would then be developed at A i.e. looked at from the right the current in A would be ant clockwise or looked at from the left, clockwise. Thus th two currents are in opposite directions.

We can arrive at the same result in another way. In Fi 38/4*a*, for simplicity, only the end coils of C and A are show On the 'C' coil, we have marked not only the direction of the current (at K), but (using the Corkscrew rule), the direction of the lines of force (FF). Now suppose C to be moved rapidly towards A. The induced current would have to be

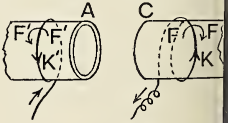


Fig. 38/4*a*

such as to set up an opposing magnetic field. The lines force would therefore have to run in the reverse directi (F′F′), and the Corkscrew rule tells us that the current wou be as indicated at K′, i.e. in the opposite direction to th of the original current.

Turning again to Fig. 38/4, let us suppose that the 'C circuit includes a switch, so that a current can be started stopped at will. The switch is open—no current. No instead of moving CD towards AB as we did before, let

lose the switch. A current suddenly starts up, with the sual attendant lines of magnetic force.

At first sight it looks rather difficult to apply Lenz's law, ut if we have not exactly moved a conductor in relation to a ıagnetic field, we have moved a magnetic field in relation to conductor, which is really the same thing. Fig. 38/4*a* will ow serve us once more. It shows the direction of the current t K), and of the lines of force (at FF) in the 'CD' coil. An pposing magnetic field will be set up in the 'AB' coil (direction ıown at F′F′), and the current to produce such a field would ıve the direction shown at K′, i.e. it would be opposed to ıe original direction.

We have dealt only with the cases where CD is suddenly ought near to AB, or where a current is suddenly started in D. You can work out the other cases for yourself (i.e. CD ddenly drawn *away* from AB, or a current suddenly *stopped* CD). In both cases you will find that the induced current s the same direction as the inducing current.

An important case arises when one coil CD is inside another B (Fig. 38/5). If the switch is osed for a moment, a current, th its attendant magnetic field, at once set up in CD. The rrent induced in AB will be such to produce an opposing magnetic ld, i.e. the induced current will ve a direction opposite to that the inducing current. All the sults we have worked out can sily be confirmed by experiment.

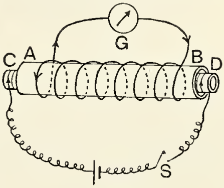


FIG. 38/5

It would be laborious, of course, if we had to *work out*, in ery case, the direction of the induced current. It is well work them out in the first instance, however, for we thereby in a much firmer grip of Lenz's law, and we then take care *remember* that

At *make*, induced current has *opposite* direction.
,, *break* ,, ,, ,, *same* ,,

 have already seen that the e.m.f. of the induced current pends on the number of turns. Hence by making the

number of turns in AB very great, we can secure a very hig e.m.f. for the induced current. We shall have an importan application of this presently in the Induction Coil.

It will be convenient at this point to set out briefly th laws which have been established relating to electro-magneti induction. For 'the number of lines of force through circuit' we shall use the shorter phrase 'magnetic flux throug a circuit.'

Laws of Electromagnetic Induction

(i) If for any reason the magnetic flux through a circu is changing, an induced current will flow round tha circuit;

(ii) The induced current will continue only so long as th magnetic flux continues to change;

(iii) The induced E.M.F. at any instant is proportional t (*a*) the rate at which the magnetic flux is changin at that instant, and (*b*) the number of turns of whi the circuit consists;

(iv) the direction of the induced current is such th its reaction tends to stop the motion which pr duced it.

Self-Induction. Consider the coil K in the figure, throu which a current can be suddenly sent by closing the switch Lines of force at once make their appearance. Their directions (given by Maxwell's Corkscrew rule) are as shown in the figure. Inside the coil they are going 'into the paper.' So far as lines of force are concerned, the effect is the same as though a magnet, with its north pole facing the coil, were suddenly pushed at the coil from the front.

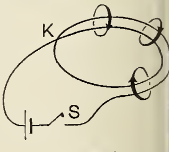


FIG. 38/6

The induction effect will be the same as though we we dealing with lines of force from this imaginary magnet—i an induced current will develop in a direction tending drive the magnet back. Such a current would have to anticlockwise—opposing the current from the battery. Th the battery current would take a longer time to reach i

naximum value, because of the opposing effect of the induced urrent.

By similar reasoning we conclude that if the current in K harply declines in value, an induced current will be set up 1 the *same direction* as the battery current. The effect in oth cases, then, is to prevent the battery current changing 1 strength as quickly as it would otherwise have done. The henomenon is known as *self-induction*.

If when a current is flowing in the circuit, we open the witch very slightly, we shall probably see a small spark cross the contacts. In this case an induced E.M.F. has een set up tending to keep the battery current going, but s the circuit is broken, this 'back E.M.F.' produces the sparking ischarge observed.

Induced Currents sometimes a Nuisance. Induced currents re sometimes a nuisance. Thus in the dynamo, induction oil and other instruments, the insulated wire of the coil is rapped round a soft iron core AB, Fig. 38/7). When a current started or stopped in the coil, 1 induced current known as an *dy* current is set up in the core, hich becomes heated. This re-esents a waste of energy. To event it, a core is made up of thin iron sheets (in the ynamo) or iron wires (in the induction coil) insulated from iother, e.g. by being varnished. There is then no continuous th presented to the eddy current.

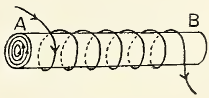


FIG. 38/7

To prevent self-induction in a coil (e.g. of a resistance box) e wire is first bent on itself, and then wound double (Fig. /19 on p. 484). You will be able to see for yourself why is method is effective.

The Induction Coil. You have probably seen an induction il in operation (Fig. 38/8), even if you have not understood ry much about it. It is very fascinating to see and hear e snapping sparks, like lightning on a small scale (the apping' is a small edition of thunder). Sometimes, after inventor, it is called a Ruhmkorff coil. Let us try to derstand how it works.

First we have the *primary circuit*. This consists of a

battery B, connected through a switch and condenser wit the *primary coil*, made up of comparatively few turns— 200, perhaps—of rather thick insulated copper wire. Insid the coil is an iron core consisting of a bundle of soft iron wires varnished so as to insulate them from one another. This cor greatly increases the magnetic field inside the coil when a current is flowing through the primary circuit. The insulation between the wires serves to prevent the formation of eddy currents. These would simply heat the core, wasting energy that would otherwise have been available for the current in the secondary coil.

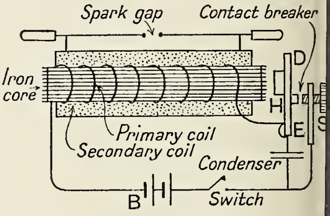


Fig. 38/8

Surrounding the primary coil, and carefully insulated fro it, is the secondary coil (shown in section in the figure). Th consists of many thousands of turns[1] of very thin insulate copper wire terminating in the two poles of the spark ga of which at least one is movable.

Notice the contact-breaker. For clearness it is show open in the figure, but it is normally closed under the actio of the spring DE, the screw S being adjusted until the surfac just touch. The contact surfaces are of platinum or tungste Let us start from this closed position. On closing the switc a current flows through the primary coil. The core becom magnetised and attracts the soft iron head H. This ope the gap at the contact-breaker, the current ceases to flo through the primary coil, and so H is no longer attracte It is carried back by the spring, closing the gap in the contac breaker, and the whole process is repeated again and again a rate depending partly on the mass of the soft iron head H and partly on the strength of the spring.

When the current is 'made' in the primary coil, a curre

[1] Coils have been made with hundreds of miles of wire on th secondaries. Some of these give sparks of 24 in. or more, indicati a voltage of perhaps 500,000.

is induced in the secondary. The e.m.f. of this induced current depends on the number of turns in the secondary, and that is why this number is made very large. The e.m.f. in the secondary also depends on the *rate* at which the primary current is made or broken. Now the current is broken much faster than it is made, and so a much higher e.m.f. is produced at 'break' than at 'make.' It is only at 'break' that the e.m.f. is sufficiently high to enable the secondary current to jump the gap (marked 'spark gap' in the figure) provided the poles are not too far apart. Thus, though the current in the secondary is intermittent, it is not alternating.

We must now consider the condenser. It consists of alternate layers of tin foil and waxed paper (p. 420), and plays an important part. Notice that in an electrical sense it lies between the surfaces of the contact-breaker, half of the tin-foil sheets (alternate ones of course) being connected with one surface, and the other half with the other surface.

When the primary circuit is broken, an induced current in the same direction is set up (self-induction). This would spark across the gap, and quickly destroy the contact surfaces. The condenser prevents, or at least greatly reduces, this tendency, for the current takes the alternative path offered to it and charges up the condenser. So far we have two advantages:

(1) Less damage to contact surfaces;
(2) 'Break' more quickly effected, and therefore a higher e.m.f. induced in the secondary (and consequently a longer spark).

But while the contacts are still separated, the charge in he condenser rushes back through the primary. If we call he original primary current left-to-right, this current from he condenser is, of course, right-to-left. Now, the e.m.f. roduced in the secondary by the *making* of a right-to-left urrent will reinforce the e.m.f. produced by the *breaking* of a ft-to-right current, and this gives us advantage (3).

The induction coil was formerly used a great deal for X-ray ork, and it is still employed for passing electricity through ases at low pressures. In our next paragraph we shall see

that the apparatus used for telephoning includes a simpl form of induction coil. 'Coil ignition,' too, used on most motor-cars for igniting the mixture of petrol vapour and ai in the cylinders is only a slightly modified form of inductio coil. In this case the contact-maker is operated by a can geared to the engine, and a distributor, also geared to th engine, controls the timing of the sparks in the cylinders. Fig

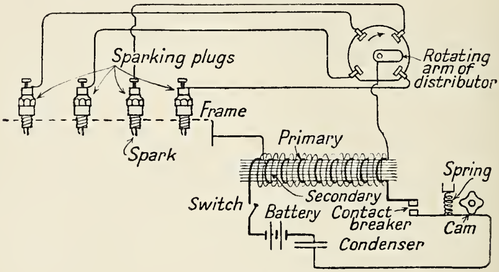


Fig. 38/9

38/9 is only diagrammatic. Actually, both primary and second ary circuits are completed through the metal frame of the car

The Telephone. As invented by A. Graham Bell in 187 both transmitter and receiver of the telephone took the form illustrated in Fig. 38/10. A horse-shoe magnet has soft iro pole-pieces projecting from each end, and these very nearly touch a diaphragm D made of thin sheet iron. Round each pole-piece is a coil of wire consisting of a great number of turns, the two coils being in series.

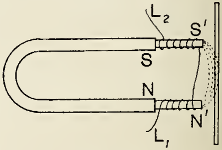


Fig. 38/10

Suppose a 'C' tuning-fork (256 vibrations per second) is sounding to the right of D in the figure. It sets up compres sions and rarefactions of the air which cause D to vibrat at the same rate as the fork. Now the lines of force passin from N′ to S′ are highly concentrated in D, and each move ment of D causes a change in the magnetic flux through th

oils. This sets up an e.m.f. which gives rise to a current in he coils, and the current passes through the line wires L_1, L_2 to a similar arrangement (magnet, coils and diaphragm) t the receiving end. Here the variation in the current 256 times per second) will produce corresponding variations f magnetic flux in the coils, and the diaphragm will move to-nd-fro 256 times per second, causing the note 'C' to be heard. Ve have considered only a simple form of vibration, but even n the case of very complex ones the diaphragm at the receiving nd copies the movements of that at the transmitting end, nd so any kind of sound (e.g. conversation) is reproduced.

The currents transmitted in the way just described are ery weak, and for distances beyond 200 niles or so, at the most, the original Bell' telephone was found to be unsuit-ble, though it is still used in a slightly nodified form as a receiver.

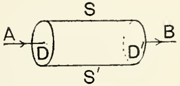


Fig. 38/11

The modern transmitter depends for s action on the principle illustrated by ig. 38/11. DD′ consists of a box filled, rather loosely, with arbon granules. D, D′, the ends of the box, are carbon lates, while the sides S, S′, are of non-conducting material. current is flowing along the path ADD′B. It is found hat if D is pushed slightly inwards so that there is better ontact between the carbon granules, there is an increase in he current because of the educed resistance. Similarly, D moves outwards, the ontact between the granules not so good, and the current reduced.

The transmitter is shown section in Fig. 38/12. The arbon diaphragm D vibrates correspondence with the peaker's voice. The granules re represented at G, and the urrent in the battery circuit, hich includes the primary oil P, varies with the movement of D as already explained.

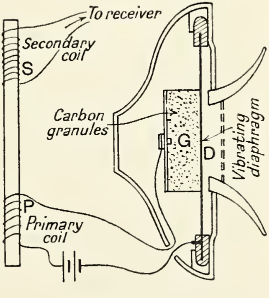


Fig. 38/12

P and S, wound over a soft iron core, form practicall the primary and secondary coils of an induction coil, S con taining many turns of thin wire. Variations of the curren in P cause much greater variations of the e.m.f. in S, an these set up a varying current, which affects the distan receiver as already described. It will be seen from th figure that it will also affect the receiver of the person telephon ing, and so he hears his own voice, but that produces n confusion.

A circuit extending over many miles (from transmitte to receiver) would have a very high resistance. If the carbo granules formed part of such a circuit, the variations in thei resistance would be such a tiny fraction of the total that th effect would not be noticed. With the arrangement jus described, however, the granules form part of a batter circuit of very small resistance, and in comparison with thi the variations caused by the changing pressure of the diaphragm on the carbon granules are quite appreciable.

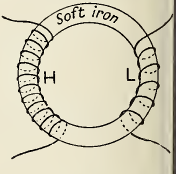


Fig. 38/13

The Transformer. This is an instrument used for converting alternating current from a low voltage to a high one ('step-up' transformer) or from a high voltage to a low one ('step-down'). Its principle will easily be understood from Fig. 38/13, which shows a ring of soft iron, round which is wrapped a coil of many turns of in sulated wire at H, and another coil of fewer turns at I H and L form parts of two distinct circuits. An alterna ing current in H sets up an alternating magnetic flux in th ring, which in turn sets up an alternating current in L. It w shown in *Junior Physics* that *the ratio of the E.M.F's i the two coils is equal to the ratio of the respective number turns.*

Transformers in actual use are usually rectangular, n circular in shape, and the core is so constructed as to avoi eddy currents (p. 493). Again, the secondary coil is usuall wound *over* the primary; and there are other differences.

Of the many cases in which transformers are employed w must mention one or two. For reasons which will be di

cussed in our next chapter, it is much cheaper to convey electric power by means of a small current at high voltage, than by a heavy current at low voltage. Hence the current produced at the generating stations, at perhaps 6000 volts, is stepped-up sometimes to as much as 132,000 volts for transmission across country by the grid system—you are sure to have seen the tall pylons associated with it.

On the other hand, the 6000 volts (say) generated at the power-station would be quite unsuitable for domestic use, so it is stepped down to 230. For operating an electric bell about 8 volts would be suitable, so we should use a trans-ormer again to step-down the 'mains' voltage from 230 o 8.

In our next chapter we shall see that the *energy* of an lectric current (expressed in *watts*) is measured by the pro-luct *volts* × *amperes*. By the law of conservation of energy here can, of course, be no increase in this product, however ve step up or step down. If a transformer were perfectly fficient, the product would remain the same, and in actual act a good transformer will have an efficiency of about 97%. 'hus vast stores of power can be transferred swiftly and ilently from one circuit to a completely independent one, ith a loss of as little as 3%—a truly wonderful achieve-nent.

The Dynamo. At the beginning of this chapter we saw that y moving a magnet in the neighbourhood of a coil of wire, r by moving a coil of wire in the neighbourhood of a magnet, e could produce an electric current. Now, the movement f which we have spoken is simply a mechanical process, and we have converted mechanical energy into electricity. hat is the essential change effected by the *dynamo*.

We saw, too, that we could predict the *direction* of the ectric current simply by taking for granted that in producing , work must be done. We could also find the direction by pplying Lenz's Law. Before going further, it will be well discuss the direction of the current in the following special se. N and S are the north and south poles of two magnets r of a single horse-shoe magnet.) The direction of the lines force is indicated by dotted lines and arrows. A straight ire AB, forming part of a circuit ABC, is moved smartly

downwards across the lines of force, as shown in Fig. 38/14 What would be the direction of the current in the wire?

The answer is given by ***Fleming's Right-hand Rule***, and should be carefully remembered. *Place the thumb, forefinger and second finger of the right-hand so as to be mutually at right angles to each other. Then if the thuMb points in the direction of Motion, and the ForeFinger in the positive direction of the lines of Force, the seCond finger will point in the direction of the Current.*

In Fig. 38/15 the right-hand is so placed as to give the direction of the current in the wire AB of Fig. 38/14. The direction of the second finger indicates that the current wil

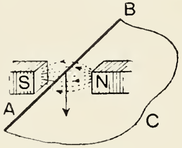


FIG. 38/14

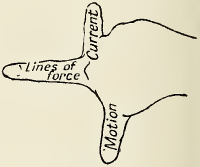


FIG. 38/15

run from A to B. We will now consider the working of the dynamo, and we shall find this 'right-hand rule' very helpful

ABCD in Fig. 38/16 (a) stands for a rectangular coil of wire lying between the poles N and S of two magnets. We are holding it at T, where the circuit is completed, and we are twirling it rapidly, in a clockwise direction, between the magnet poles. Everything is drawn in plan.

With the coil in the position of Fig. 38/16a, the right-hand rule tells us that the direction of the current would be along AB and CD. (Do not simply *read* this, try it for yourself. Thus in the case of CD, your right thumb must point downwards—the direction of motion, and your forefinger from left to right. You will find that your second finger is then pointing in the direction CD.)

The current will maintain the direction ABCD so long as AB is moving upwards (and CD downwards)—i.e. until the coil is in the position of Fig. 38/16b. In that position, AB and CD are not *cutting* the lines of force, but are moving along them. There is therefore no current at all.

Next consider Fig. 38/16*c*. The coil has made half a ɘvolution from the (*a*) position. AB is now moving downwards, nd CD upwards. The right-hand rule tells us that the urrent is now running from B to A, and from D to C (preiously it was from A to B and from C to D respectively). n fact, it is in the reverse direction from that shown in Fig. 8/16*a*.

When did this change take place? Clearly, when AB egan to move downwards—i.e. at the moment it was passing ırough the (*b*) position. So long as AB continues to move ɔwnwards—i.e. until the position of Fig. 38/16*d* is reached,

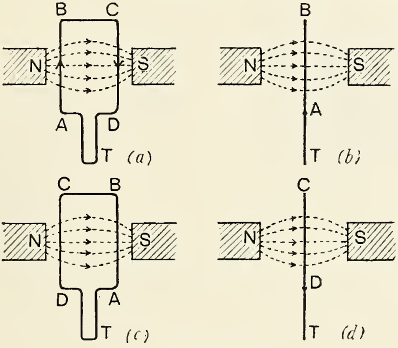


Fig. 38/16

th CD at the top—the current will retain this 'BADC' ection. When AB once more begins to move upwards— . as soon as the (*d*) position is passed—the current will verse once more, taking the original direction ABCD.

So far, then, the position is this. While AB is moving wards (position (*d*), through (*a*) to (*b*)) the current has the ection ABCD. While it is moving downwards (position , through (c) to (d)), it has the reverse direction; and the ange takes place each half-revolution, at the moment ıt the plane of the coil is at right angles to the direction the lines of force.

Let us look more closely into the matter. Is the change

sudden or gradual? Have we a current of unvarying streng all the time that AB is moving up, then a sudden drop zero, followed by a current of the same unvarying streng but in the opposite direction?

To answer this we recall that since the coil has a consta resistance, say R, the current is proportional to the E.M. ($C = E/R$), and the E.M.F. in turn is proportional to t rate at which the coil is cutting through the lines of for Evidently, then, we have to consider this last point.

A diagram will help us. In Fig. 38/17, AD represents t coil looked at from the front (and so hiding BC). T

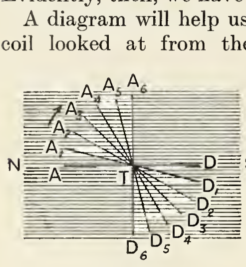


Fig. 38/17

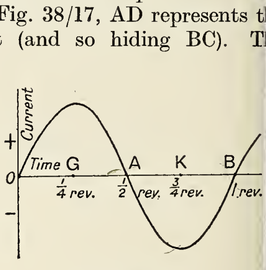


Fig. 38/18

equidistant parallel lines represent lines of force. The c is supposed to be revolving at a uniform rate, so its positi after equal intervals of time is shown by the lines A_1 A_2D_2, etc.

By counting, we find that in moving from AD to A_1D_1 has cut through ten lines of force (five between A and and five between D and D_1), from A_1D_1 to A_2D_2 throu eight lines, from A_2D_2 to A_3D_3 through six, and so on throu less and less, until in the neighbourhood of the A_6 positi it is not cutting through any at all, but is moving paral to them.

Thus the current is strongest when the coil is cutting t lines of force at right angles—i.e. when the plane of the c lies in the direction of the lines of force—and it falls off unt when it has moved through 90°, the current is zero, aft which it reverses. The state of things is expressed graphical in Fig. 38/18, which shows how the current varies in t course of one revolution. After this the curve is repeat

gain and again. It can be proved that the curve is a *sine urve*—i.e. that the strength of the current is proportional o the sine of the angle through which the coil has revolved rom the 'zero current' position.

Such a current, changing its direction every half-revolution, known as an *alternating current* ('A.C.'). The complete ound of changes that takes place with one revolution is nown as a *cycle* and the number of cycles per second is called e *frequency*. A.C. from the mains is normally '50 cycles'— e. it has a frequency of 50 cycles per second. Obviously e current changes in direction twice in the course of one volution, so that the number of alternations is twice the

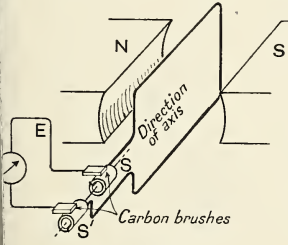


FIG. 38/19

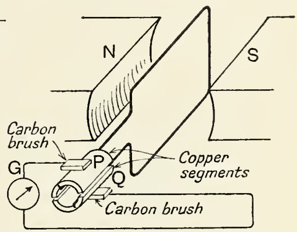


FIG. 38/20

mber of cycles. The machine producing such a current known as an *alternator*.[1]

Our machine so far is not a very practical instrument. To gin with, we need some means of conveying the current an external circuit. To do this, we have two *slip-rings*, S′ in Fig. 38/19, mounted on the same axis as the revolving il, but insulated from it. The two ends of the coil are dered to these slip-rings, one to each. A carbon *brush* esses against each slip-ring, and these brushes form the rminals of the external circuit E.

Suppose we want to convert our alternating current into direct one? This is done by means of a *commutator*, a nple form of which is known as the *split-ring* commutator.

[1] It is often called a *dynamo*, but the latter term is more correctly plied to a Direct Current Machine (also known as a *Generator*).

As in the case of the slip-rings just mentioned, it is mounte on the same axis as the revolving coil, and is insulated fro it. Its two segments, P, Q (Fig. 38/20), are also insulated fro one another. The two brushes previously mentioned woul now press against the two halves of the commutator, on brush to each half. Each brush is so placed that just as th current is changing in direction, it makes contact with different half of the commutator.

Keep in mind that P is *permanently* in connection (b soldering) with one terminal of the coil (and, of course,

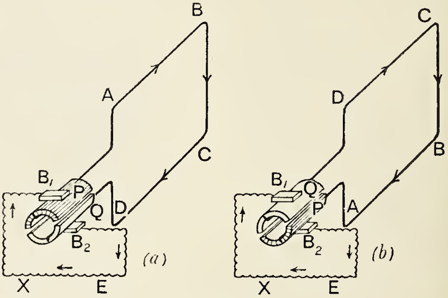


FIG. 38/21

with the other), and so every half-revolution the current th reaches P will change in direction.

In Fig. 38/21*a* the current is flowing from P to Q (via th path ABCD). It leaves Q by the brush B_2, and trave through the external circuit in the direction B_2EXB_1.

Half a revolution later we have the state of things repr sented in Fig. 38/21*b*. P is now in contact with B_2 and with B_1. The direction of the current *in the revolving c* is reversed, its direction now being from Q via DCBA to It leaves P by the brush B_2, thence via EX to B_1, and so ba to Q. Thus its direction *in the external circuit* is B_2EXB_1- the same as before.

But though with the device just explained we have su ceeded in getting a *direct* current, we have not obtained

teady one. Representing it by a curve (OCADBE, Fig. 38/22), it is now entirely above the horizontal, its strength arying from zero (at O, A, B . . .) to a maximum (at C, D, E . . .). We could improve matters by having two coils, t right angles, so that one would be giving its maximum urrent while the other was giving its minimum. With this rrangement we should need four commutator segments nstead of two. The currents from the two coils are shown in he figure, one with a thin, unbroken line (OCADBE) and the ther with a dotted one (FGHKLM). By adding the ordinates e obtain a curve (FNCPHQ . . .) representing the *combined* urrent—e.g. TX = TV + TW. This is better than before, ut is still far from eady. The curve YZ epresents the current btained by using five oils, the individual urves, however, being mitted for clearness. here is still an obous 'ripple' but the ariation, WY, is small comparison with the tal current OW, and becomes less and less

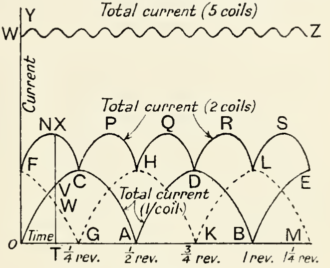


FIG. 38/22

the number of coils is increased. However, a full discuson of this part of the subject would take us too far afield.

A few words must be said about the 'winding' of a dynamo. small instruments the 'field magnet'—i.e. the magnet oducing the necessary magnetic field—consists simply of permanent horse-shoe magnet. Usually, however, it nsists of an electro-magnet, which, of course, has to be excited passing an electric current through the *field coils*, round its les. In some cases the winding of the field magnet is nply included in the external circuit—i.e. the entire current sses round the field magnet—and the dynamo is said to be *ies wound.* (At first, of course, there is no current, d it looks as though the dynamo would never start. tually there is always sufficient residual magnetism in the le pieces to set the process going.)

More commonly, alternative paths are presented to thi current as it leaves the brushes. One path is via the fiel coils, the other constitutes the external circuit. The dynam is then said to be *shunt wound.* The two methods of windin are illustrated in Figs. 38/23 and 24.

There is also a method of winding ('series shunt' or 'com pound') which includes both the above types.

In our account of the dynamo we have constantly referre to a rotating coil consisting of a single turn. In practice, c course, the coil consists of many turns, and there are usuall a number of coils. Further, in order that the lines of forc cut by the coil may be as numerous as possible, we provide them with an iron path—the coils, in fact, are wound on an iron cylinder, built up, as already mentioned, of thin plates of iron, insulated from one another to prevent eddy currents. This revolving part of the instrument is known as the *armature.* However, our purpose in this chapter has been simply to explai the broad principle on which a dynamo works, and no to give a full description of the instrument as actuall used.

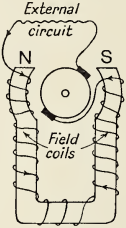


Fig. 38/23

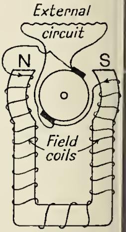


Fig. 38/24

Ammeter for A.C. It is often necessary to measure alte nating current, i.e. we need a suitable *ammeter.* A hot-wi ammeter (to be described on p. 525) may be employed, or w may use what is called a *moving iron ammeter* (Fig. 38/25) i which the current passes through the circular coil shown, an in so doing magnetises two soft iron cylinders, B and F, bot parallel to the axis of the coil. One of them, F, is fixed, whi the other, B, is joined to a needle pivoted at P and movin over a scale. Whether the current is direct or alternatin the cylinders are magnetised with like polarity, and so B repelled by F, causing the needle to move over the scale.

Effects of Alternating Current. We should expect th

alternating current, like direct current, would produce heating, magnetic and chemical effects. The first of these is obvious enough in an electric fire, or when we handle an electric light bulb which has just been in use. For a reason which should be obvious, we can *not* show the magnetic effect by placing the 'wireless' flex over a compass needle and switching on. We can however carry out the iron filings experiment illustrated by Fig. 36/5 on p. 454. We need stout copper wire, say 2-mm. diameter, and A.C. of at least 30 amperes, previously stepped down to 12 volts or so.

To illustrate the chemical effect we can (with certain modifications) employ the apparatus represented in Fig. 34/2 on p. 424. 'S' however is replaced by a source of alternating

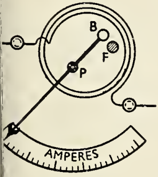


FIG. 38/25

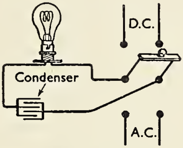


FIG. 38/26

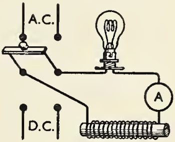


FIG. 38/27

urrent, either the 'mains' supply stepped down to 30 volts, or a ow voltage supply stepped up to that figure. The resistance is so adjusted that the ammeter records about 0·4 amps. test-tube T_1 should be placed over E_1 (corresponding to $_2$ over E_2).

We cannot now regard one electrode as anode and the other s cathode, for each is anode and cathode in rapid alternation. he result is that in each test-tube there collects a mixture of wo volumes of hydrogen and one of oxygen.

Alternating Current and Condenser. Fig. 38/26 shows a mp in series with a condenser, a switch being so arranged at either direct or alternating current can be supplied. 'ith D.C. the lamp does not glow, but on switching over to C. it does. The condenser acts as a reservoir of electricity, hich quickly fills up when we are using direct current, and en the current ceases. With alternating current, however,

the reservoir fills and empties with each reversal of current, and so an alternating current flows through the lamp.

The Choke Coil. With the arrangement of Fig. 38/27, either direct or alternating current can be passed through a circuit which includes a small lamp, an ammeter which will work on either D.C. or A.C., and a coil of insulated wire inside which is an iron core.

Using direct current, we find that the glowing of the lamp and the reading of the ammeter, are not affected by the presence or absence of the core. With alternating current however, the current is greatly reduced when the core is completely inside the coil, gradually increasing as it is withdrawn.

The variation is a consequence of the self-induction of the coil (p. 500). Every time the current changes direction, an opposing E.M.F. is set up, and this reduces the current just as would the insertion of a resistance. If an iron core is introduced, it becomes magnetised, giving rise to additional lines of force. When these are being produced (or, at reversal of current, withdrawn), they cut the turns of the coil, and greatly add to the opposing E.M.F. mentioned above.

The total resistance offered to an alternating current—i.e. the ordinary resistance that would be offered even to a direct current *plus* the special resistance called into play by inductance—is known as the *impedance*. In an A.C. circuit of given voltage, the current is often cut down by introducing a coil of high inductance, known as a *choke*, or *choke coil*. The resistance offered by such a coil to a direct current may be quite low.

Principle of the Motor. In the alternator or dynamo we compel a coil of wire to rotate in a magnetic field, with the result that an electric current is produced. It seems not unreasonable to expect that if we pass an electric current through a coil placed in a magnetic field, the coil will rotate. That is found to be the case, and it is this production of movement by an electric current that is the essential feature of the electric motor.

Faraday's experiment, in which, however, we have a straight wire and not a coil, is easily repeated. The arrangement of the apparatus will be clear from Fig. 38/28*a*. When a current is passed, the wire turns round and round (in a clockwise direction if the current is passing

lown the wire as in the figure). If the direction of the current is reversed, the wire rotates in the opposite direction.

In Fig. 38/28*b* the north pole of the magnet is shown in plan, with some of the lines of force. The little circle with a cross represents the current travelling downwards. The direction of motion is given by ***Fleming's Left-hand Rule***, which may be thus stated. *Place the thumb, first finger and second finger of the left hand so as to be mutually at right angles to each other. Then if the* ***F****irst* ***F****inger points in the direction of the lines of* ***F****orce, and the se****C****ond finger in the direction of the* ***C****urrent, the thu****M****b will point in the direction of* ***M****otion* (Fig. 38/29).

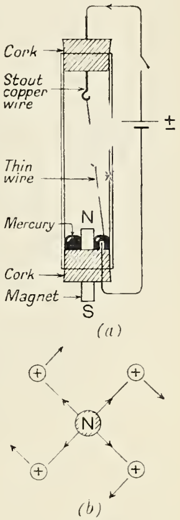


Fig. 38/28

N.B. If you find yourself confused between the Right-Hand Rule and the Left-Hand Rule, this will help. The driver of a *motor* (car) keeps to the *left*—and this *Left* Hand Rule is the *Motor* Rule.

Try this rule with reference to Fig. 38/28*b*, and you will find it leads to the conclusion that the wire should be driven round in a clockwise direction.

Now let us reconsider the case of a coil of wire between two magnet poles, but from the 'motor' point of view. In Fig. 38/16 on p. 509 we were forcibly turning the coil, and a cur-

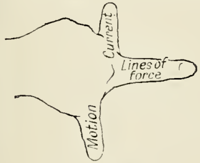


Fig. 38/29

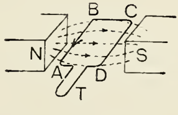


Fig. 38/30

rent was induced in it. This time we are sending a current through the coil, with a view to making it turn. If we pass the current *from A to B* we soon find by the Left-Hand Rule that the coil would turn anti-clockwise. Let us make it go

clockwise. The current will have to be in the opposite direction—i.e. from B to A. In what follows we shall find it more convenient to have a *front* view (Fig. 38/31*a*). B and C will be invisible, being 'covered' by A and D. The dot in A means that the current is coming through the paper *towards* the observer, while the cross in D means that it is going away from him.[1]

Keeping the current in this direction, the Left-Hand Rule tells us that A would continue to move upwards until AD is vertical. By its own momentum we may suppose that it would go a little beyond that point—say, to the position shown in Fig. 38/31*b*. Now, *making no change in the direction of the current* (i.e. at A let it still be coming towards you as in Fig. 38/32*a*) apply the rule once more. You find that the

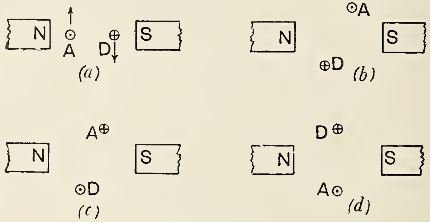


Fig. 38/31

motion would now be in the opposite direction—the coil would begin to move anti-clockwise. Clearly, if we wish it to continue moving clockwise, we must reverse the direction of the current at the moment when AD is at right angles to the lines of force—i.e. when AD is vertical; and so we get the state of affairs indicated in Fig. 38/31*c*. With this direction of current, rotation will continue to be clockwise until A has reached the bottom position (Fig. 38/31*d*). If it is to continue clockwise we must once more reverse the current.

Summing up the position, we see that if the coil is to continue moving in a given direction, the current must be reversed every half revolution, at the time when the plane of the coil

[1] Think of an arrow coming towards you. You see the *point* represented by a dot. When it is going away from you, you see the feather end, represented by a cross.

s at right angles to the lines of force. We secure this result ›y arranging that the current shall pass into the motor hrough a commutator, a simple form of which (the split ing commutator) has already been described. Speaking enerally, in fact, a machine that can be run as a dynamo an also be run as a motor. Motors, too, like dynamos, are lassified according to their method of winding into *series ›ound*, *shunt wound* and *series-shunt* (or *compound*) *wound*.

From what has been said, it would seem that to drive a ıotor we should need direct current (with a commutator for eversing it at each half revolution). In general this is true, ut a series-wound motor may also be driven with alternating ırrent. The reason is that in this case the same current asses through both the field coils (exciting the magnets) ıd the armature (the revolving coils). Thus, when the ırrent changes direction, it changes direction in both at

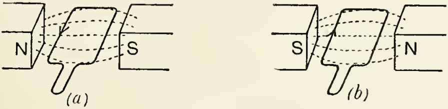


FIG. 38/32

e same time, the net result being the same as if it had not anged at all. If this is not quite clear, apply the Left-and Rule first to Fig. 38/32*a*. In Fig. 38/32*b* the current is versed, causing the field magnet to have reversed polarity, d so causing the lines of force to run from right to left stead of from left to right. In both cases the Left-Hand ıle shows that the coil will be turned clockwise.

If a current is passed through a small motor and then through ne lamps arranged in parallel, it will be found that as the ›tor gathers speed, the lamps grow dim. The reason is at when a motor is in action, it inevitably behaves like a namo as well as like a motor. After all, the coils of the nature are cutting through lines of force (just as in the namo)—it makes no difference in this respect whether the ls are driven by mechanical power or electric power. Thus Lenz's law an e.m.f. tending to stop the motion is set up. is reverse e.m.f. is known as the *back e.m.f.* of the motor,

and, of course, the faster the armature revolves, the stronger this back e.m.f. becomes. If the applied voltage is E and the back e.m.f. is e, the current at any instant is given by $C = \frac{E-e}{R}$. To begin with, e is, of course, zero. As it rises in value, C becomes less.

Thus a current which might safely be passed into a freely running motor (because it is reduced in the way just discussed) might do serious damage if passed in at the beginning, when the coils are at rest. The difficulty is overcome by having a special resistance known as a *starting resistor* in circuit with an arrangement whereby, as the motor speeds up, more and more of this resistance is cut out.

Questions

1. If you were provided with two coils of insulated wire, a galvanometer, a Leclanché cell, a magnet and some connecting wire, how would you demonstrate the elementary phenomena of electro-magnetic induction?

Describe one important application of electromagnetic induction in everyday use. *Dur.*

2. State a law for the direction of a current set up by electromagnetic induction and describe an experiment to verify the law. *Lond.*

3. State the laws of electromagnetic induction.

A coil of wire is rotated at a uniform rate about an axis at right angles to a strong uniform magnetic field. How does the E.M.F. vary with the angle between the coil and the magnetic field? State at what positions of the coil the E.M.F. is (a) a maximum, (b) a minimum.

Also show in a diagram how the direction of the induced current is related to the directions of movement and of the magnetic field.

How may the simple arrangement described above be modified to give a direct current in the external circuit? *Camb.*

4. State the laws of electromagnetic induction.

Describe a simple form of induction coil and explain, without reference to the action of the condenser, how it is possible by means of it to produce a very large voltage across its spark-gap although the source of energy is a battery of only a few cells. *Dur.*

5. What is Lenz's law? Apply the law to find the direction of the induced current in a cylindrical coil of wire when a bar magnet is brought up to the coil along the axis, with the north pole towards the nearer end of the coil.

Draw a diagram of an induction coil and explain its action. *Brist.*

6. Describe the construction, and explain the action, of the transmitter and the receiver of the simple telephone.

7. How could you reduce an A.C. voltage of 200 to one of 20 volts? *O.C.**

8. Describe a method of producing an alternating current.

If an alternating current supply of known E.M.F. were available, how would you transform it to one at (*a*) a higher E.M.F., (*b*) a lower E.M.F.? What change would you expect to take place in the magnitude of the transformed current in each case? Give reasons. *Dur.*

9. Describe a simple alternating current generator.

Explain the difference between an alternating and a direct current and how it is possible to distinguish one from the other in practice. What is the chief advantage of alternating over direct current? *Camb.*

10. Describe, with the aid of a diagram, a simple form of series wound direct-current electric motor. Explain briefly how it works.

Indicate how you would reverse the direction of rotation of the armature. *Oxf.*

11. A loose wire hangs vertically between the poles of a strong electro-magnet. State clearly, and also show on a diagram, how the wire tends to move relatively to the magnetic field when a current flows in the wire. *Camb.*

12. Explain why the current which passes through the armature of an electric motor is greater when it is starting to turn than when it is turning rapidly. *Camb.**

CHAPTER 39

ELECTRICITY AS ENERGY

One of the prominent features of an electrical generating station in England is the large amount of *coal* that is constantly being taken in. It is used for producing steam to drive steam turbines, and these, in turn, drive the alternators ('dynamos') which generate the electric current on the principle discussed in the preceding chapter—by compelling coils of wire (enclosing cores of soft iron) to revolve against opposing forces set up by a magnetic field. In short, we have one form of energy, *heat* (from coal) converted into the *kinetic energy* of the steam turbine and of the dynamo, which in turn is converted into *electricity*. It looks very much as though electricity were simply another form of energy, and we are confirmed in this idea when we notice how it can do mechanical work (e.g. in driving the street car or operating a lift), or can give rise to heat (e.g. in the electric fire).

In Chapter 21 we found that there was a definite *quantitative* relationship between heat and work, viz. 1 British Thermal Unit = 746 ft.lb. In the present chapter we shall see that there is also such a relationship between electricity and heat, and therefore between electricity and work.

It is very easy to think of work as being measured in foot-pounds. We do a foot-pound, of course, when we lift a mass weighing 1 lb. through a vertical height of 1 ft. and if our pound weight falls a foot it does work equal to 1 ft.lb.

The work that can be done by a mill-stream (in driving a water-wheel, for instance) depends on the *weight* of water that falls and on the *difference of level* of the water before falling and afterwards. Suppose, for instance, that 11,000 lb. of water fall 5 ft. every second, the work done is 11,000 × 5 or 55,000 ft.lb. per second. This is the *rate* of doing work or as we call it, *the power*.

Have we anything parallel to this in electricity? A

convenient unit of quantity in electricity is the *coulomb*, while *difference of potential* or *voltage* (measured in volts) corresponds to the difference of water level—the 'fall.' Just as a pound weight falling a foot does work equal to 1 foot-pound, so a coulomb falling in potential by a volt does a quantity of work which might perhaps have been called a volt-coulomb, but is actually known as a *joule*, a joule being equal to 10^7 ergs (p. 212).

In the 'water' case worked out above, the power was expressed in ft.lb. per sec. (usually converted to horse-power by dividing by 550). In the electric case, suppose we have a current of C amperes (i.e. a current which carries C coulombs per second—p. 426), and the voltage is E. Then since 1 coulomb falling 1 volt does work = 1 joule, C coulombs falling E volts does work = CE joules. That is the work done per second, i.e. it is the *power*. The unit of power (1 joule per second) is known as the *watt*. In short, then, a current of C amperes with a fall of potential of E volts has a power or rate of working of CE watts, or CE joules per second.

When we pay an electricity bill, we are really paying for the amount of *energy* consumed. This is arrived at by taking account of: (i) the *rate* at which the energy is being used (as we have seen, this can be measured in watts, but the practical unit is 1000 watts, called the kilowatt), (ii) the *time* measured in hours. These two together give us the ***kilowatt hour***, defined as *the energy supplied in one hour by a circuit working at the rate of* 1000 *watts*.

It is very useful to be able to reckon, quickly, the cost of using electric lights, fires, immersion heaters, etc. We must, of course, know the price per 'unit' (i.e. per kilowatt-hour). Suppose this is a penny. Then a 100-watt lamp in 1 hour uses $\frac{1}{10}$th of a k.-h. costing $\frac{1}{10}d.$; so it gives us 10 hours' light for a penny. An electric fire taking 3 kilowatts would cost 3d. per hour, and so on.

In Chapter 21, where we considered the relation between heat and work, we saw that 1 calorie = 4·2 joules, or 1 joule = 0·24 calorie. Thus a current of C amps. at E volts, if converted into heat (e.g. by passing through a wire) would produce heat at the rate of $EC \times 0{\cdot}24$ calories per second.

Example 1. *A current of* 5 *amp. at* 230 *volts is used to heat a litre of water in an electric kettle. Assuming that all the heat goes into the water, and the latter is at* 16° *C., how long will it be before the water boils?*

$$\text{Heat required to boil 1000 gm. of water} = 1000 \times (100 - 16) = 84{,}000 \text{ cals.}$$

$$\text{Heat produced per sec. by electric current} = EC \times 0{\cdot}24 \text{ cals.} = 230 \times 5 \times 0{\cdot}24 = 304 \text{ cals.}$$

$$\therefore \text{no. of secs.} = \frac{84{,}000}{304} = \mathbf{5\ min.\ 4\ sec.}$$

We have seen that the power of a current in watts, or joules per second, is given by the product EC. This may be expressed in another way, for by Ohm's Law, $C = E/R$, and therefore $E = CR$. Thus instead of $E \times C$ we may write $CR \times C$ or C^2R (i.e. joules per second, or watts). Expressed in calories per second, this would be $C^2R \times 0{\cdot}24$, and the heat produced in t seconds would be $C^2Rt \times 0{\cdot}24$ calories.

If this expression is correct, we ought to be able to prove that the heat produced by a current is proportional to (i) the time, (ii) the resistance, (iii) the square of the current. We can do this by experiments such as the following.

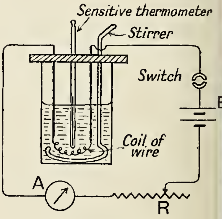


Fig. 39/1

A complete calorimeter is used, though only the inner vessel (covered with a slab of wood) is shown in Fig. 39/1. In the slab holes are bored and through these pass (i) a thermometer reading to fifths of a degree C., (ii) a stirrer, (iii) two pieces of stout copper wire, connected at the bottom with a coil of very thin, insulated wire, preferably made of nichrome or German silver. The coil of wire forms part of a circuit, which also includes an ammeter A, an adjustable resistance R, a battery B, consisting of two or three 2-volt accumulators connected in series, and a switch.

(i) *To show that heat produced is proportional to time.*

Take the temperature of the water at intervals of 1 minute. It will be found to rise uniformly, showing that the heat produced is proportional to the time. Plotting temperature against time you should, of course, obtain a straight line.

(ii) *To show that heat produced is proportional to resistance.*

Take a coil of wire twice as long as before, cut from the same reel. This will have twice the resistance. Now repeat the last experiment using the adjustable resistance to keep the current to the same strength as before, and continuing the experiment for the same time. It should be found that the rise of temperature is twice as great. Other ratios may be tried.

(iii) *To show that heat produced is proportional to square of current.*

With a given coil inside the calorimeter carry out two experiments, adjusting the external resistance so that the current in the second experiment is twice what it was in the first. The time for each experiment must be the same, say 5 minutes. It should be found that with *twice* the current we obtain *four times* the rise of temperature, and therefore four times the amount of heat (since the mass of water was the same in each case). Ratios other than 1 : 2 may be tried, and it is a good plan to plot the rise of temperature against C^2, when a straight line should be obtained.

Hot-wire ammeter. This depends for its action on the fact that a wire is heated when a current passes through it. ACB is such a wire. At C it is connected with another wire CED, fixed at D. When ACB is heated by the current, it sags, and this would cause CED to become slack. But CED is connected at E with a thread which passes round the pulley P and is attached to the spring S. This thread and spring keep CED taut. The more ACB expands, the more is CED pulled on by the spring and thread, and the more is the pulley P turned. A pointer attached to P moves over a graduated scale as shown in Fig. 39/2.

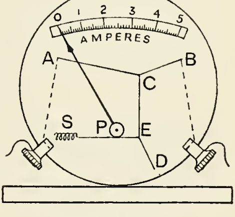


FIG. 39/2

The heating of the wire is, of course, quite independent of the direction of the current, and so a hot-wire ammeter can be used for measuring alternating current.

At this stage let us consider a few more calculations based on the formulae previously mentioned in this chapter. Many of them obviously have a practical bearing.

Example 2. *Describe an experiment to show the relation between the heat generated in a current-carrying wire and the current passing through it.*

A certain heating coil of resistance 50 *ohms can carry a maximum current of* 5 *amp. Calculate* (a) *the number of calories of heat generated per minute in the coil when on maximum load,* (b) *the cost of the electrical energy used per day of* 24 *hours at twopence per kilowatt-hour.* Lond.

For first part of question, see preceding page.

(a) No. of calories per second $= C^2R \times 0{\cdot}24$.

$\therefore$ no. per minute $= C^2R \times 0{\cdot}24 \times 60$
$= 5^2 \times 50 \times 0{\cdot}24 \times 60$
$= \mathbf{18{,}000}$

(b) Power in watts $= C^2R = 5^2 \times 50 = 1250$
$= 1{\cdot}25$ kilowatts

$\therefore$ electrical energy used in 24 hours $= 1{\cdot}25 \times 24$ kilowatt-hours.

$\therefore$ cost at $2d.$ per k.h. $= 1{\cdot}25 \times 24 \times 2$ pence
$= \mathbf{5s.}$

Example 3. *Define the* watt *and the* joule.

If an electric kettle contains a 1000-*watt heating unit, what current does it take from* 230-*volt mains? How long will the kettle take to raise* 1000 *gm. of water at* 15° *to the boiling point, if* 90% *of the heat produced is used in raising the temperature of the water? How much would this cost if the charge is one penny for a kilowatt-hour?*
Camb.

For first part of question, see pp. 521 and 212.

To find the current. *Volts* $\times$ *Amps.* $=$ *Watts.*

$\therefore$ *current (amps.)* $=$ *watts* $\div$ *volts*
$= 1000 \div 230$
$= \mathbf{4{\cdot}35}$ ***amps.***

Heat produced per sec. $=$ *watts* $\times 0{\cdot}24 = 240$ cals.

Of this, only $90\% = \frac{9}{10}$ of 240 or 216 cals. per sec. is used in heating the water.

No. of cals. required to raise 1000 gm. from 15° C. to boiling point $= 1000(100 - 15) = 85{,}000$.

$\therefore$ time required $= 85{,}000 \div 216 = 394$ secs. $=$ **6** ***mins.*** **34** ***secs.***

Cost. 1000 watts for an hour (3600 secs.) costs $1d.$

$\therefore$ 1000 „ „ 394 secs. costs $\frac{394}{3600}d.$ or $\mathbf{0{\cdot}109}\boldsymbol{d}.$

***Example* 4.** *Explain what is meant by the statement that the resistance of a wire is* 10 *ohms.*

Calculate the resistance of a machine which takes 1000 *watts at* 200 *volts. What power would be used in the machine if it were connected* (a) *in series with a* 10*-ohm resistance* (b) *in parallel with the resistance, and the combination were connected in each case to a* 200*-volt supply?* J.M.B.

For first part of question see p. 468.

Resistance of machine $E \times C = 1000$

But $E = 200$

$\therefore \quad C = 5$ amps.

By Ohm's law $C = E/R \; \therefore \; R = \dfrac{E}{C}$

$\therefore \qquad R = 200 \div 5 =$ **40 ohms.**

(a) In series with 10-ohm resistance,

total resistance $= 10 + 40 = 50$ ohms.

$\therefore C = E/R = 200/50 = 4$ amps.

$\therefore$ power $= EC = 200 \times 4 =$ **800 watts** or **0·8 k.w.**

(b) If the machine (resistance 40 ohms) were in parallel with a 0-ohm resistance, only $\frac{1}{5}$th of current would pass through achine (p. 475, footnote).

Combined resistance R is given by $\dfrac{1}{R} = \dfrac{1}{40} + \dfrac{1}{10}$ giving $R = 8$ ohms.

$\therefore C = E/R = 200/8 = 25$ amps.

Current passing through machine $= \frac{1}{5}$th of this $= 5$ amps.

$\therefore$ power $= EC = 200 \times 5 = 1000$ watts

$=$ **1 kilowatt.**

***Example* 5.** *A battery of E.M.F.* 4·5 *volts and internal resistance ohms has its terminals connected in turn by wires of resistance ohm and* 4 *ohms respectively. Compare the rates at which heat is nerated in the two wires.*

In first case total resistance (wire + battery) $= 1 + 2 = 3$ ohms

$\therefore \quad$ current $= E/R = \dfrac{4{\cdot}5}{3} = 1\frac{1}{2}$ amps.

In second case total resistance $= 4 + 2 = 6$ ohms.

$\therefore \quad$ current $= E/R = \dfrac{4{\cdot}5}{6} = \dfrac{3}{4}$ amp.

Now heat produced in wire $\propto C^2R$

$$\therefore \quad \frac{\textit{heat produced in 1st case}}{\textit{heat produced in 2nd case}} = \frac{\left(\frac{3}{2}\right)^2 \times 1}{\left(\frac{3}{4}\right)^2 \times 4} = 1$$

i.e. heat is generated at **equal rates.**

Example 6. *The wires leading to a group of six glow-lamp arranged in parallel have resistance 1 ohm and the lamps have eac a resistance of 60 ohms. Calculate the ratio of the heat develope in the lamps to that developed in the leading wires.* Dur.*

Since the lamps are in parallel, the resistance of the group wil be $60 \div 6 = 10$ ohms

Leading wires have resistance of 1 ohm.

Since heat produced $\propto C^2R$ and the same current passe through the leading wires, and the *group* of lamps

$$\frac{\textit{heat produced in lamps}}{\textit{heat produced in wires}} = \frac{C^2 \times 10}{C^2 \times 1} = \frac{10}{1}$$

i.e. required ratio $= \mathbf{10 : 1.}$

Example 7. *On what factors does the heat generated in a con ductor by an electric current depend? Write down an expression for i*

Ten accumulators, each of E.M.F. 2 volts and internal resistanc 0·5 ohm, are to be charged from 100-volt D.C. mains. Draw diagram of the circuit used, calculate the extra resistance required to maintain the charging current at 0·8 amp., and find how much heat is generated per minute in each accumulator (J = 4·2 joules per calorie). Camb.

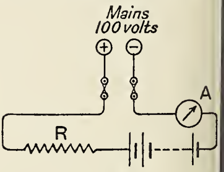


FIG. 39/3

For first part of question see p. 522. Fig. 39/3 shows the circuit diagram.

Resistance. The accumulators provide an opposing E.M.F. of $10 \times 2 = 20$ volts.

$\therefore$ the effective voltage for the circuit is $100 - 20 = 80$ volt

Total resistance will be given by R in the equation $C = E/R$ where $C = 0{\cdot}8$ and $E = 80$.

$\therefore R = 80 \div 0{\cdot}8 = 100$ ohms.

Of this, $10 \times 0{\cdot}5 = 5$ ohms is provided by the accumulators.

$\therefore$ extra resistance required $= 100 - 5 =$ **95 ohms.**

Heat generated per minute in each accumulator is given b

$$H = \frac{C^2Rt}{4{\cdot}2} \text{ cals., where } C = 0{\cdot}8,\ R = 0{\cdot}5 \text{ and } t = 60.$$

$$\therefore H = \frac{0{\cdot}64 \times 0{\cdot}5 \times 60}{4{\cdot}2} = \mathbf{4{\cdot}57 \ cals.}$$

Transmission of electric power. In the preceding chapt it was mentioned that when electric power has to be tran mitted over great distances (e.g. by the 'grid' system) it

first stepped-up to a high voltage. We can now see the reason for this. At the generating station, suppose the current produced has a strength of C amp. at 11,000 volts. It is stepped up, say, to 132,000 volts. There is of course no increase in power, otherwise we should have a violation of the law of Conservation of Energy; so as the voltage goes up to twelve times its previous value, the current falls from C to $\frac{1}{12}$ C.

Now suppose the original current (C amp.) had been transmitted through a wire of resistance R ohms.

Heat produced per second, $h_1 = C^2R \times 0{\cdot}24$ cal.

In transmitting the stepped-up current,

Heat produced per second, $h_2 = (\frac{1}{12}\,C)^2R \times 0{\cdot}24$ cal.

$$\therefore \quad \frac{h_2}{h_1} = \frac{(\frac{1}{12}\,C)^2R \times 0{\cdot}24}{C^2R \times 0{\cdot}24} = \frac{1}{144}.$$

Thus the heat lost in transmission, using the higher voltage, only 1/144th part of what it would have been at the lower.

Theoretically, there is another way (i.e. instead of stepping p) of reducing the loss of heat to 1/144th of its original alue. We could do it by reducing the resistance. To do is, we should need a wire of 144 times the cross-sectional ea, and the weight would be so enormous as to make the ethod impracticable.

Questions

A

1. An electric kettle takes a current of 5 amp. at 200 volts. what rate is it taking electrical energy?

2. Describe an electrical experiment that you have either rformed or witnessed to show that 1 calorie of heat is equivalent 4·2 joules of work.

An electric heater is marked '240 volts, 1500 watts'; calculate its resistance when in use, (*b*) the quantity of heat produced 5 minutes, and (*c*) the cost of running the heater for 5 hours, price of electrical energy being $1\frac{1}{2}d.$ per Board of Trade it (kilowatt-hour). *C.W.B.*

3. In the kettle of question 1, how many calories would be duced in 1 min, 40 sec.? (1 calorie = 4·2 joules).

. A lamp is rated at 230 volts, 60 watts. What does this ing indicate? What current does the lamp take and what is resistance? Find the cost of using this lamp for 500 hours if cost of electrical energy is 3*d*. per unit. *Lond.**

5. A wire of resistance 10 ohms carries a current of 15 amp. How much heat would be produced in 20 sec.?

6. An alternator is maintaining a current of 10 amp. at 100 volts. By means of a transformer the voltage is stepped up to 10,000. Assuming there is no waste of energy in the process what would be the new value of the current?

7. If in the last question the current is passing through a wire of resistance R, how much heat is dissipated per second in the wire, (i) before the process of stepping up, (ii) afterwards?

8. A lamp is marked 240 V., 100 W. What current will it take? What is its resistance? How many hours of light will it give for a penny, assuming that the cost of electrical energy is 2*d*. per Board of Trade unit?

9. An electric fire when full on takes 3 kilowatts. Find the cost of running it for 4 hours, at $\frac{3}{4}$*d*. per kilowatt hour.

B

1. Describe an experiment which would show how the ratio of rates of production of heat in each of two coils of wire when the same current is sent through them is related to the resistance of the coils. What result would you expect?

Compare the rates of production of heat when an electric heater is used on a 220 and on a 200-volt circuit, assuming the resistance to be the same in each case. *J.M.B.*

2. An electric lamp is marked 100 W., 240 V. Calculate (a) the strength of the current passing through the filament, and (b) the resistance of the filament, when in use in the appropriate circuit. Would you expect the resistance of the filament to have the same value when cold? Give reasons.

If three such lamps are connected in parallel in a 240-volt circuit, calculate (*a*) their equivalent resistance, and (*b*) the cost of running the lamps for 75 hours when the cost of electric energy is $5\frac{1}{2}$*d*. per kilowatt-hour. Give a diagram of the circuit showing the positions of lamps, switches, and fuses. *C.W.B.*

3. A current of 2 amp. passes through a resistance consisting of two coils of resistance 4 ohms and 6 ohms respectively, arranged in parallel. Calculate (*a*) the equivalent resistance of the coils, (*b*) the current in each coil, (*c*) the heat in calories developed in each coil in 5 minutes. How would you test the last result experimentally? *Lond.*

4. Deduce an expression for the heat developed in a conductor due to the passage of a steady electric current.

Two wires of the same cross-section have specific resistances in the ratio of 2 to 1. The wire with the larger specific resistance is *three* times the length of the other. Compare the heats developed in the two wires when they are placed across the mains in (*a*) series, (*b*) parallel. *O.C.*

CHAPTER 40

WIRELESS AND RADIOLOCATION

[T]HE working of the familiar wireless set depends partly on principles with which we are already familiar, partly on some that will be new to us. In the following pages we shall recall the familiar principles and endeavour to make the new ones clear; and though within our limits of space we cannot give anything like a full discussion of the subject, we may hope to give a good idea of its broad outlines.

Suppose we have some water in the U-tube of Fig. 40/1. By tilting the tube, closing the left-hand limb with a finger, and then restoring it to the upright position, we can easily

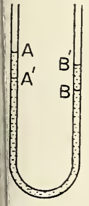


FIG. 40/1

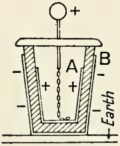


FIG. 40/2

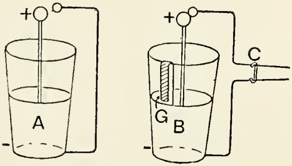


FIG. 40/3

arrange that the level at A is higher than at B. On removing the finger, the levels are not restored at once. The left-hand column falls, but overshoots the mark, falling to A′, while B rises to B′. This 'overshooting' is repeated a number of times before the two columns are at the same level.

It has been proved that a similar situation arises when a Leyden jar is discharged (Fig. 40/2). The charged surface A is connected with the uncharged surface B. A spark is seen as the discharge takes place, but the discharge is really *oscillatory*. There is a rush of electricity from one surface to the other, then a back-rush and so on, until the two surfaces are at the same *electric* level—i.e. at the same potential.

Next consider the experiment represented in Fig. 40/3.

A and B are two similar Leyden jars, but the inner coating of B is continued by a strip of tin-foil, and brought over the top to finish near the outer coating, the gap at G being less than a millimetre. C is a sliding contact, so that we can alter the length of the circuit between the inner and outer coatings.

A is charged, then discharged—and we watch the gap at G. Most likely nothing happens. We alter the position of C and repeat the charging and discharging. By and by we find that, *for a certain position of* C, a spark appears at G when A is discharged.

We are reminded very much of the *resonance* that may be produced by a tuning-fork. If a tuning-fork A is sounded near another one B, B will be set in vibration provided it has the same frequency as A (p. 337). In the case of the tuning-fork, the *prong* oscillates. In the case of the Leyden jar, the *electrons* are oscillating. The fork sets up sound waves in the air. The electric discharge sets up some sort of waves in space.

What is the nature of these waves?

To begin with, it was found out many years ago that they travel at the same speed as light—300 million metres per second. The difference lies in their length. Thus while light waves have a length of about 4 to 8 ten-thousandths of a millimetre (the exact length depending on the colour), the waves of which we are speaking commonly have a length of from 1 to 20,000 metres, though very much shorter ones, down to a fraction of a millimetre, have been produced.

Again, when the condenser is charged, all its energy is in the electric form. Now we already know that when an electric current passes along a wire, a magnetic field is set up in the space surrounding the wire. Similarly during the first rush of the oscillatory discharge, a magnetic field is set up in the neighbourhood, and there is a moment when all the energy is in the magnetic form. When the first rush is complete, the energy is once more in the electric form, and so on. Thus the oscillatory discharge corresponds to the alternate production of electric and magnetic fields, and the waves given off are known as *electromagnetic waves*. Fig. 40/3*a* will help to indicate the similarity of these waves to those which produce light of different colours, and to the infra-red and

ultra-violet waves.[1] It shows also that X-rays and gamma-rays belong to the same family (so do the rather mysterious cosmic rays).

It would be quite impossible by using an ordinary scale to show all these waves on the same diagram. Suppose for instance that to represent the light waves—the visible part of the spectrum—we used a scale in which a micron is represented by 1 cm. (a micron = 1/1000th mm., and light waves vary in length from about 0·4 to 0·8 microns). The entire range of gamma rays would be invisible because they would be represented by only 1/700th mm., while to show the waves commonly used in wireless we should need a length of 6,000

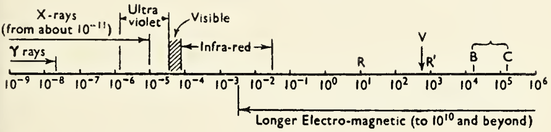


FIG. 40/3*a*

niles or so. However, by using a *logarithmic* scale, i.e. one n which our scale is proportional to the logarithm of the wave-ength—we are able to make a very fair representation.

A wave-length of about 6 metres (V in Fig. 40/3*a*) is used for elevision. For broadcasting, the B.B.C. uses wave-lengths anging from 206 to 1,500 metres (BC in figure), while wave-engths of from about 10 to 1000 cm. (RR′) are employed in adar.

At various parts of the scale we notice overlapping. Thus the hortest electromagnetic waves are exactly similar to the longest nfra-red, though the former are produced by means of a triode alve, while the latter are present in radiation from the sun.

To return to our experiment with the Leyden jar. This hows that the waves thereby produced can set up correspond-g waves in a neighbouring circuit provided the latter has been

[1] For infra-red waves see pp. 199, 200. Ultra-violet rays are very tive chemically. Thus they rapidly affect a photographic plate, and their action on the skin cause 'vitamin D' to be produced just below Further, they cause *fluorescence*—we have an example in the curious uish appearance of paraffin oil. The oil absorbs the very short waves d gives out longer ones—long enough to give a colour effect.

suitably *tuned*—and here we have the underlying principle of 'wireless.'

In the experiment of Fig. 40/3 most of the energy of the discharge is used up to furnish the heat, light and sound of the spark, and very little is available for furnishing electro-magnetic waves. The path of discharge should include an appreciable *inductance*—a coil in which a magnetic field is set up as the current passes through it. Again, Marconi showed that much better effects are obtained if one plate of the condenser is connected to an 'aerial' and the other to the earth. For our oscillatory discharge much better results would be obtained by using, instead of a Leyden jar, a high-frequency alternator in conjunction with a transformer. These ideas are embodied in Fig. 40/4. The two parallel lines represent a condenser. This allows a good supply of electric energy to be stored up in our transmitting circuit. The arrow represents provision for tuning.

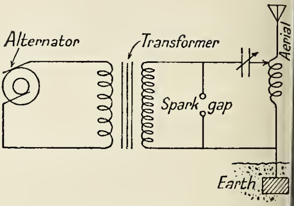


FIG. 40/4

Our 'receiving' circuit would be similar, except that, of course, we should have no need for the alternator and transformer. It can be show that the frequency with which such a circuit 'resounds,' so t speak, is equal to $\frac{1}{2\pi\sqrt{LC}}$, where L and C represent th inductance and capacitance respectively, expressed in suitabl units. We mention this formula only as a reminder th we can alter the frequency by altering either the inductanc or capacitance, or both. Usually we alter the latter, th condenser concerned being usually of the form shown in Fi 33/23 (p. 420).

So far we have mentioned only one means of finding wheth waves have been received by the second circuit—the pro duction of a spark (as at G in Fig. 40/3). We need somethin much more sensitive. Could we not make the current, as oscillates in the second circuit, operate a telephone?

Unfortunately, no—not with the arrangement as so far described. The oscillations are far too rapid to affect the comparatively slow-moving diaphragm of the telephone.

Let us examine these oscillations a little more closely. As we have seen, they accompany a spark, and gradually die away. In Fig. 40/5, A represents the oscillations accom-

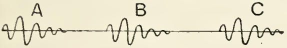


FIG. 40/5

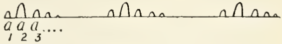


FIG. 40/6

panying a single spark. The fact that the electrons move first in one direction and then in the other is indicated by drawing part of the wave above the line, the following part being below it. The alternations are shown as gradually dying away to zero—we say they are 'damped.' The complete figure represents the effect of three successive sparks.

Now it is possible (by means which we will consider presently) to allow the current to pass in one direction only, so that instead of Fig. 40/5 we have Fig. 40/6. Accompanying

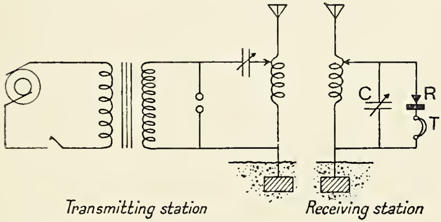


FIG. 40/7

a single spark we now have a series of pushes at the diaphragm (a_1, a_2, a_3 . . .), varying in intensity, but all in the same direction. We may therefore regard them as merging into a single push. The frequency of these single 'pushes' is therefore equal to the frequency of the sparks, and this is *not* too high to produce vibration of the diaphragm. Thus if the sparks were produced at the rate of 256 per second, we should have a note of 'middle C' pitch in the telephone.

If in the circuit which includes the alternator, etc.—the transmitting circuit—we include a key, we can start and stop the telephone note in the receiving circuit at will, and we could obviously use a Morse code to transmit messages. The complete arrangement is represented diagrammatically in Fig. 40/7, C being a condenser of adjustable capacity, T a telephone, and R an arrangement for 'rectifying' the current, i.e. for allowing it to pass in one direction only.

We must now take up this question of how the current is rectified. It was formerly done by inserting a suitable crystal in the circuit. Certain crystals—galena, for instance—when touched by a fine metal point, show a conductivity much greater in one direction through the point of contact than in the reverse direction, so that for practical purposes they allow the current to pass in one direction only. Such an arrangement is represented diagrammatically by R in Fig. 40/7. Instead of a crystal, however, a valve is now almost universally employed. We will first explain the principle of the *diode valve*, invented by the late Sir Ambrose Fleming.

Its action depends on the fact that when a metal filament is heated, it throws off electrons. In practice a tungsten filament F is used, surrounded by a copper cylinder P (Fig. 40/8*a*), both filament and cylinder being contained in an evacuated bulb. For diagrammatic purposes the cylinder (or 'plate') is usually represented as in Fig. 40/8*b*.

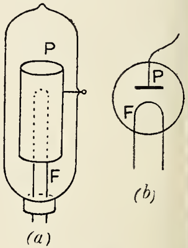


Fig. 40/8

Now suppose P forms part of an *oscillating* circuit. It will be charged positively and negatively in rapid alternation.

(i) When it is positively charged, the electrons (negative electricity) thrown off from F will be attracted. But a flow of negative electricity from F to P corresponds to a flow of positive electricity from P to F (Fig. 40/9). Thus we have a current in the direction PF—the gap serving as a conductor because of the electrons present in it.

(ii) When P is negatively charged, the electrons from F will be repelled, and so there will be no current.

Thus what would have been an oscillating current is converted by the valve into a unidirectional current—from P to F.

As we have seen, the arrangements so far described would serve for the transmission of signals such as Morse, but would certainly not transmit conversation or music. For one thing, the sounds of conversation or music are continuous, and it is difficult to see how they could be reproduced by discontinuous waves such as we have described.

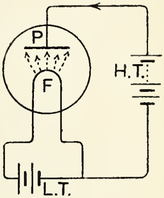


FIG. 40/9

However, methods have been devised for producing continuous electromagnetic waves such as those represented in Fig. 40/10*a*. They are, of course, of radio frequency, and are known as *carrier waves*. The line HL joining the crests of the waves is horizontal. By means which we cannot discuss here, it is possible to combine such waves with sound-waves, so that the line joining the crests is the wave form of the sound we are producing. Thus a tuning-fork produces a wave of very simple form (Fig. 40/10*b* on p. 535), and when this is combined with the waves first mentioned, we get a result such as is represented in Fig. 40/10*c*, except that the carrier waves should be much closer together. When a wave of this sort is rectified by cutting out the lower half, it affects the loud speaker in such a way as to reproduce the original sound. The sound waves of conversation or music are often very complex indeed, but they are imposed on the carrier waves in the same way.

Even in such a brief discussion as this, we must give some account of how waves which would be too feeble to affect a wireless set are *amplified*. For this a triode valve, shown diagrammatically in Fig. 40/11, may be used.

The special feature of this valve is the *grid*, a third electrode coming between the plate and filament of the valve previously described. In practice it consists of fine copper gauze, or a spiral of thin wire.

It acts in this way. Suppose we have a plate current passing in the direction PF, as already described. The grid is made part of the circuit in which the feeble oscillating current is flowing. The potential of the grid is therefore varying all the time, though only slightly.

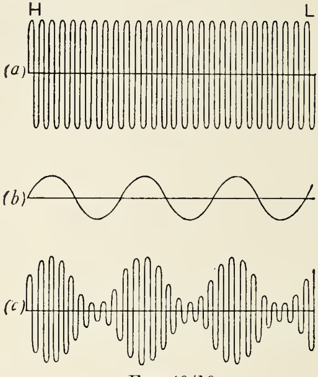


FIG. 40/10

Now, when the grid has a slight positive potential, the flow of electrons from F to P is greatly encouraged, and so there is a great increase in the strength of the plate current. When it has a slight negative potential, the flow of electrons is

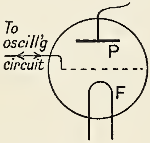


FIG. 40/11

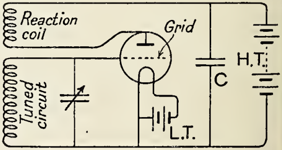


FIG. 40/12

greatly reduced, and so there is a marked decrease in the plate current. Thus, instead of the feeble variations of the original current, we have a plate current showing strong variations. In short, our triode valve has acted as an *amplifier*.

The Valve Transmitter. Consider the circuit of Fig. 40/12. Here the plate current is made to pass through a *reaction coil*, and a weak alternating current is supposed to be passing through the tuned circuit. This weak current causes slight changes in the potential of the grid, which in turn gives rise to much greater changes in the energy of the plate current. As the latter passes through the reaction coil, the current in the tuned circuit is increased (by induction). This is now able to produce greater changes than before in the strength of the plate current, and so on—the action is cumulative.

By reducing the distance between the reaction coil and the tuned circuit ('increasing the coupling' is the usual phrase), we can still further increase the effect just described. Now, an increase of current in the tuned circuit is the same result as would follow from a reduction of its resistance (Ohm's Law). By suitably adjusting the coupling, we can reduce this effective resistance to zero, and a current set up in the tuned circuit will now circulate indefinitely, since there is no resistance, so to speak, to stop it. Such a condition is known as *oscillation* (the chief cause of 'howling' in a wireless set).

By adjusting the condenser (capacity), or the inductance, we can alter the frequency of the tuned circuit. Thus we have the means of generating an alternating current of adjustable frequency, which is just what we need for transmitting. The transmitting aerial has only to be connected to the tuned circuit, and the alternating current from the latter then provides the energy which is transmitted into space. Valve transmitters based on the principles just briefly described are used by all broadcasting stations.

Having discussed the use of the triode valve as an amplifier for transmission purposes, let us now go back to the point (p. 538) at which we saw that it could be used as an amplifier in the receiving set. This amplified current may be still further amplified by another valve, and so on, until finally it enters the moving coil of a

Loud Speaker (Fig. 40/13). This consists of a very light coil wound on a short cardboard tube attached to a paper cone, and it moves between the poles N, S of an electromagnet. The direction of the current in the coil is evidently at right angles to the lines of force between N and S, so the coil moves

in and out in accordance with Fleming's left-hand rule. As a result the paper diaphragm, or cone, gives vibrations corresponding to those which originally struck the microphone at the transmitting end, and so the original sounds are reproduced.

Radiolocation. We have seen that 'wireless' waves differ from light waves only in the matter of length, and, as we should expect, they are subject to the same laws of reflection and refraction. An important method for finding the position of distant objects, aeroplanes, for instance, is based on the reflection of electromagnetic waves, and is known as *radiolocation* or *radar*.

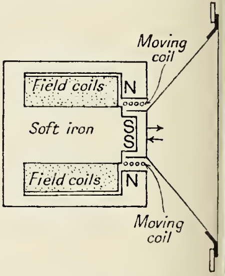


FIG. 40/13

The transmitter and receiver are in this case in the same place, and usually have the same aerial, or 'antenna,' as it is called in radar. The antenna can be moved easily into any desired direction. Suppose it is pointed at an aeroplane, and the 'modulator' is turned on (this causes the radio-frequency oscillator to oscillate violently for a millionth of a second or so). Waves are thus sent out, strike the aeroplane, and are reflected to the receiver. This contains a device by which the time required for the to-and-fro journey is automatically recorded with an accuracy of about one-thirtieth of a millionth of a second. Suppose the time in this case is 1/100,000th part of a second. Now, as the waves travel 186,000 miles per second, they would travel 1·86 miles in the 1/100,000th part of a second. This is, of course, the distance to the aeroplane and back again, so the required distance is 0·93 mile. (The observer does not work this out—a spot of light moves to the correct number on a scale.)

Normally, of course, the aeroplane would not be visible at all. The antenna is moved about until a signal (known as a 'pip') is observed on the receiver. The direction of the object is now given by that of the antenna, and the distance is recorded as already described. The time is so short that

the aeroplane will not have made any appreciable movement, and gunfire can be as effective as if it were visible.

The transmitter does not send out waves continuously, but in very short bursts of a millionth of a second or so, followed by comparatively long intervals of rest (a few thousandths of a second), during which the receiver is in action. If very long waves were used, the instrument would not be able to distinguish between two objects very close together, so the aim has been to use wave-lengths as short as is practicable.

It is quite possible that radar turned the scale in the battle of Britain (1940), when our margin of safety was certainly a very narrow one. Without it, our pilots would have had to be in the air all the time to be ready for a possible attack, and they would have been worn out. As it was, they could remain grounded and resting, knowing that they would receive timely warning of an attack.

Radar was much used by the Army and Navy (especially the latter) during the war, as well as by the Air Force. For instance, 'On the evening of 4 November 1942 . . . the sea battle for Guadalcanal was in its final phase, the issue still undecided. Aboard the American vessel, radar, like an invisible searchlight, probed the darkness and discovered the presence of an enemy vessel more than eight miles away. The big ship lifted its gun muzzles towards the stars. They flashed and thundered. The second salvo, despite both darkness and extreme range, landed squarely on the target, which disappeared from the radar screen.' [1]

Happily, the uses of radar are not limited to the operations of war. A captain, for instance, near a fog-bound coast can 'see' the contour of the coast. He can ascertain the position of other ships in the neighbourhood, and of rocks, buoys, lighthouses, etc. He can steam ahead almost as confidently as though the sun were shining in a clear sky.

[1] From 'Radar; a Report on Science at War.'

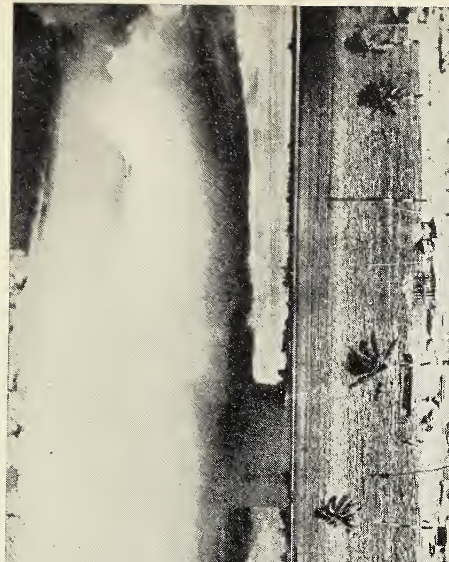
CONCLUSION

ATOMIC ENERGY

MOST people study Physics for a long time before they realise that what they are studying is chiefly *energy* in its various forms. Clear examples of this are seen in Electricity, Heat and a large part of Mechanics. In England our main source of energy is coal, and to a much less extent oil. The same is true for many other countries, though some (e.g. Norway) make great use of water-power. The energy required for blasting in quarries and coal-mines is obtained from explosive compounds, which again have their origin, partly or completely, in coal; and the same is true of the explosives used in war.

But on Aug. 6th, 1945, the world was startled by reading of the unparalleled havoc caused by a single bomb which fell at Hiroshima in Japan, causing the almost complete destruction of a large town and killing 80,000 people—more than had been killed in all the towns of Britain by all the air-raids of the war. Its destructive energy was derived, it was explained, not from any of the usual sources, but from the disruption of atoms of uranium; it was the Atom Bomb. Later, for experimental purposes, an atom bomb was dropped at Bikini in the South Pacific, to explode under water, and the illustration gives some idea of the remarkable visible effect produced. In this chapter we shall try to understand something of the nature of this new source of energy.

On p. 402 it was explained that atoms are the ultimate particles of which elements are composed, each element having its own special kind of atom. We saw, too, that these atoms are incredibly small. Until 1898 people thought of them as being something like tiny billiard balls—i.e. something 'the same all through'—without any particular structure. In that year, however, there was discovered an element, radium, which behaved in a very peculiar way. It was constantly throwing off 'alpha-particles,' really atoms charged with positive electricity, of another element called



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EXPLOSION OF ATOM BOMB AT BIKINI

helium. In addition, it was throwing off negatively charged particles called electrons.

Our first thought is, of course, 'Then radium cannot be an *element*; it must be a compound of helium.' But though it would take us too long to consider the evidence, it is quite certain that radium *is* an element, and, like any other element, is made up of atoms. The fact is that the atoms of radium are constantly undergoing a kind of decomposition that is known by the special term of *disintegration*. The atom of radium, then, is *not* 'the same all through.' Almost infinitely tiny as it is, it is built up of still tinier parts, which include electrons and positively charged atoms of helium.

Another very important point arises in connection with the disintegration of the radium atom. Much *energy* is released. It is found that the alpha-particles of which we have spoken are given off with a velocity of something like 20,000 miles per second, and as these tiny but enormously swift projectiles strike the surrounding medium, they are slowed down or stopped, their kinetic energy being converted into heat. One gram of radium will produce about 140 calories per hour. The radium is gradually used up in the process—converted into helium and other products—but the process is so slow that it would take about 1700 years for *half* of it to disappear. It is not a very difficult problem in arithmetic to calculate the amount of heat produced by the disintegration of one gram of radium. It works out to about 2640 million calories, enough to raise the temperature of 31 tons of water from room temperature to boiling point. Of course this heat is given out over a very long period of time, but when we recall that it is produced from a quantity of radium weighing very much less than a sixpence, the amount is astonishing.

However, let us leave details on one side and get a clear grip of the essential point, which is that *by the disintegration of atoms of radium, enormous quantities of energy are released.*

The fact that the radium atom was constantly undergoing the change just discussed made it certain that it must possess a complicated structure—it was no mere 'billiard ball.' Men soon began to suspect that *all* atoms had a structure following the same general design, and after much patient work they

had by the year 1932 arrived at the ideas which have already been outlined on p. 402, but which we must now consider in rather more detail.

In our earlier chapter something was said about protons and neutrons. The mass of each of these is about equal to that of a hydrogen atom. The proton carries a unit of positive charge, but the neutron is uncharged. It may be that it is really made up of a proton firmly combined with an electron, the positive charge of the one cancelling out the negative charge of the other.

The nucleus is made up of at least these two kinds of particles, protons and neutrons. The nucleus of the helium particle, for instance, consists of two protons (P in Fig. C/1) and two neutrons (N), with a total mass of four (calling the mass of the hydrogen atom one). This nucleus, because of its two protons, carries two positive charges. The helium atom *as a whole*, however, is electrically neutral, and this neutrality is secured by two electrons (*e*), whose two negative charges balance the two positive ones. Fig. C/1 represents the state of affairs diagrammatically, except that the distance from the nucleus to the electrons should be very much greater.

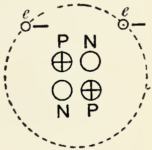

FIG. C/1

The number of electrons surrounding the nucleus varies from one atom to another. The hydrogen atom includes only one electron, the helium atom two (as already mentioned), the lithium atom three and so on, until the largest number is found in the case of uranium which has ninety-two. The number of electrons is known as the *atomic number* of the atom in question. Thus the atomic number of helium is two, while that of uranium is 92.

The *atomic weight* of an element is numerically equal to the sum total of the neutrons and protons in the nucleus, the mass of one of these being taken as the unit. Thus helium has an atomic weight of four. The mass of an electron is only about 1/1800th part of the mass of a proton (or neutron), and so in comparison may be neglected. From what has been said we should expect all atomic weights to be whole numbers, since the nucleus must contain a whole number

of protons and neutrons. If we look at a table of atomi weights, we shall find that though many of them are whol numbers, this is by no means true of all. Chlorine, fo instance, has an atomic weight of 35·47. The reason i that there are really two different atoms included under th name chlorine. In one there are 17 protons and 18 neutrons giving an atomic weight of 35, while in the other there ar 17 protons and 20 neutrons, giving an atomic weight of 37 Ordinary chlorine is a mixture of these two *isotopes* (as the are called), in such proportions as to give an atomic weigh of 35·47. The two 'chlorines' are chemically identical That is because each has the same number of electrons, fo it is the number of electrons in the atom of an element whic determines its chemical properties. We shall see presentl that ordinary uranium consists of a mixture of *three* isotopes with atomic weights of 234, 235 and 238 respectively. I each case there is the same number of electrons (92), so al three have the same chemical properties. Further, th nucleus in each case contains 92 protons, the positive charge on which balance the negative charges on the electrons. Th remainder of the atomic weight is, of course, contributed b the neutrons. Thus 'uranium-234' contains 234 − 92 or 14 neutrons, while uranium-235 contains 143, and uranium-23 contains 146.

The neutron was not recognised until 1932, though it ha been produced several years earlier (without being recognise by mixing radium bromide with a rather rare metal know as beryllium. Apparently alpha-particles thrown off by th radium struck some of the nuclei of the beryllium atom knocking out one or more neutrons from each. The neutro is, of course, very small, but it may have a velocity of som thousands of miles per second; so scientists thought it woul be very interesting to use these neutrons as projectiles wit which to bombard the nuclei of other atoms. They ha methods (which we cannot discuss here) of recognising whe they had 'made a hit.' They found that sometimes th projectile buried itself in the nucleus which it had struck but in certain cases it broke the nucleus into two or mor fragments, other neutrons being set free in the process. Bu there was something far more important than the mer

breaking of the nucleus, and that was the release of energy (chiefly in the form of heat) which accompanied it. In the case of uranium this release of energy was to have very remarkable consequences.

Let us put it in this way. Suppose a quantity of uranium is divided into sections A, B, C, . . . Z (Fig. C/2). A neutron, say from the radium–beryllium mixture, strikes A and dislodges two fresh neutrons. We now have a total of three. Before reaching B one of them may be lost, perhaps escaping at the sides, or perhaps being absorbed in a nucleus like a bullet sticking in a clay bank. However, while only one neutron struck A, we have two striking B, and these dislodge (say) four fresh neutrons. Four plus two = six. Allowing for wastage, suppose four neutrons strike C, causing eight to strike D, and so on. Before long, the number of neutrons striking a section is enormous, and *the release of energy is correspondingly great.*

Fig. C/2

What we have sketched out is known as a *chain reaction.* Obviously it is very similar to a spreading fire, and it may get completely out of hand.

Before going further, let us grasp the point that a chain reaction from the arrangement indicated in Fig. C/2 is by no means inevitable. It might be that of 100 neutrons released from A, after allowing for losses by escape, absorption, etc., only 90 would strike B (a loss of 10%), and if this rate of loss continued only 81 would strike C, and so on. Instead of the fire spreading so to speak, it would gradually die out. Now let us see what happened in practice.

Uranium 'fission,' as it is called, was well known to prominent physicists all over the world as early as the beginning of 1939, at a time when war-clouds were already gathering. What was *not* known was whether a chain reaction could be established. If it could, there was the possibility of constructing a bomb whose destructive energy would far exceed that of any existing high explosive. Thus while British and American scientists were at work on the problem, they were well aware that German scientists were engaged on it, too. Defeat in the laboratory might well bring national downfall in its train.

Research on an enormous scale was instituted, and we may notice one or two of the problems to be solved.

It has already been mentioned that uranium as extracted from natural ores consists of a mixture of U-234, U-235 and U-238. Of these, it is only the U-235 [1] that is readily fissionable, and commercial uranium contains only about one part in 140 of this particular isotope. When we recall that there is no difference in *chemical* properties between one isotope and another, we begin to see how difficult it must be to extract U-235 from the mixture.

Before attempting to make a bomb, it was necessary to find whether a chain reaction was possible. At this stage, precautions had to be taken against the possibility that the reaction, if it occurred, might get out of hand. One precaution was to arrange for a slowing down of the neutrons. This was done by the use of a very pure carbon as a 'moderator,' the 'slugs' of metallic uranium being embedded in the carbon. The neutrons struck the nuclei of the carbon atoms and were slowed down. In addition, arrangements were made for *absorbing* some of them if necessary. For this purpose, bars of cadmium were used, which could be drawn out or pushed in according as a more or less vigorous reaction was desired. The *pile* (as the whole arrangement was called) did not at first give a chain reaction, but by increasing the proportion of U-235, and adjusting the arrangements for moderating and absorbing, success in this respect was achieved.

To be effective, a bomb must not be below a certain minimum size (known as the 'critical size'). The reason is that the smaller the size, the greater is the area in comparison with the volume. Now, a large area favours escape of neutrons, and in a bomb of less than critical size the proportion of escaping neutrons is so great that a chain reaction is not possible. No information has been published about critical size, except that it apparently lies between 1 kilo and 100 kilos.

Let us now turn from our discussion of the atom bomb and consider the far more important question of whether atomic energy can be used as a source of power for ordinary peace-time purposes.

[1] U-238 however (which forms 99·3 per cent. of purified natural uranium) may be converted into plutonium, which is fissionable.

One obvious difficulty has just received mention—the unit must not be of less than a certain size. Further, a chain-reaction pile gives off rays which would quickly prove fatal to anyone receiving them, and so far it has been necessary to surround the pile with a shield of concrete 5 ft. thick. Still another difficulty is that the energy from the pile would probably in the first instance be used to heat water, which would soon become dangerously contaminated. These are just a few of the difficulties that must be surmounted before atomic energy can be utilised as an everyday source of power, and they suggest that the first units are likely to be large ones, serving perhaps as central generating stations or providing the source of power for a large works. Possibly too, an ocean liner might be driven by atomic energy. It seems unlikely however that it will ever be possible to use such energy in cases where it would have to be produced on a very small scale, say for driving a motor car or even a locomotive.

But even taking into account all the practical difficulties, it will surely be no very long time before man will have made atomic energy his main source of power. The world's great industrial nations will then not necessarily be those possessing great natural supplies of coal, oil or water-power, but those best served by their scientists and technologists—and in this respect our own outlook is a very hopeful one. Man will look back upon the days when he hewed his coal from grimy pits much as we look back upon the Stone Age, for he will have at his disposal sources of power, clean in operation and unlimited in extent, which may well provide the physical basis for a development and culture as yet undreamed of.

But at the same time he would be living in a fool's paradise if he did not contemplate the ghastly alternative, and take steps to obviate it. The power that, rightly used, can enable the human race to advance towards new heights of achievement and culture, can also reduce it to the lowest depths of misery, and may come within measureable distance of exterminating it altogether. The discovery of how to release atomic energy was a great achievement, but if it is to be a blessing and not a curse it must be followed by a still greater one—the devising of means whereby all the nations of the world may live at peace one with another.

ANSWERS TO NUMERICAL EXERCISES

Answers to the odd-numbered questions only have been given

Chapter 32, p. 397

A

1. (i) 1 dyne; (ii) 1 dyne; (iii) 4 dynes. **3.** 3 dynes.

B

1. 4 cm. **3.** (*a*) 225 webers; (*b*) 450 units (of moment) per c.c.
5. 1 : 2. **7.** 0·235 oersted. **9.** 0·181 oersted.
11. 0.195 oersted. **13.** 0·193 oersted.

Chapter 33, p. 421

9. 4 dynes.

Chapter 34, p. 439

1. 0·148 gm. **3.** 1·22 amps. **7.** 1·35 amps.
9. 4 hr. **11.** 0·0000104; 0·000328. **13.** 0·0011 amp.
15. Copper gains 0·178 gm., zinc loses 0·183 gm.

Chapter 35, p. 450

3. 0·614 gm.

Chapter 36, p. 465

B

5. 0·57. **7.** 0·286. **9.** 36°.

Chapter 37, p. 489

1. 1·43 amp.; 1·07 amp. **3.** 32·07 m. **5.** 0·75 ohms.
7. (*a*) 2·4 ohms; (*b*) 1·2 amps. in 4-ohm coil, 0·8 amps. in 6-ohm. **9.** 3 ohms.
11. (*a*) 2 volts; (*b*) 12 volts; (*c*) 1·2 amps. in 1st (10-ohm), 0·8 amps. in 2nd.
13. (*a*) $3\frac{2}{3}$ ohms; (*b*) 0·41 amp.; (*c*) 0·27 amp. (1-ohm branch), 0·14 amp. (2-ohm branch).
15. $\frac{1}{2}$ ohm. **17.** (*a*) 0·68 amp.; (*b*) 0·68 volt; (*c*) 0·41 amp.
19. 3·2 ohms. **21.** Put resistance of 98 ohms in series with it.
23. (*a*) 4·2 volts, 15 ohms; (*b*) 1·4 volts, $1\frac{2}{3}$ ohms.
25. 0·3 amp.; 1·2 volts.
27. (*a*) 0·253 ohm and 1·500 ohms; (*b*) 0·289 volt.
29. 1·5 volts, 0·5 ohm.

Chapter 39, p. 527

A

1. 1 kilowatt. **3.** 23,810. **5.** 10,800 cals.
7. (i) 24R cals.; (ii) 0·24R cals. **9.** 9*d*.

B

1. 1·21 : 1. **3.** (*a*) 2·4 ohms; (*b*) 1·2 amps., 0·8 amp.; (*c*) 415 cals., 276 cals.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	·0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	·0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	·0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	·1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	·1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	·1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	·2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	·2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	·2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	·2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	·3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	·3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	·3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	·3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	·3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	·3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	·4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	·4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	·4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	·4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	·4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	·4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	·5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	·5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	·5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	·5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	·5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	·5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	·5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	·5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	·6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	·6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	·6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	·6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	·6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	·6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	·6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	·6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	·6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	·6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	·6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	·7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	·7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	·7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	·7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	·7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	·7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	·7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	·7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	·7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	·7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	·7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	·7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	·7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	·8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	·8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	·8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	·8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	·8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	·8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	·8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	·8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	·8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	·8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	·8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	·8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	·8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	·8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	·8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	·8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	·9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	·9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	·9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	·9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	·9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	·9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	·9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	·9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	·9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	·9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	·9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	·9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	·9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	·9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	·9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	·9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	·9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	·9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	·9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	·9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

INDEX

N.B. *The principal references are indicated by* **heavy type**

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